THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

AN ASSESSMENT OF MULTIPLE SEAM MINE STRESS CONDITIONS USING A NUMERICAL MODELLING APPROACH

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SUMMARY

Underground coal mining in Australia has primarily focussed on mining the single most economical seam though many may exist within a lease area (Gale, 2004). The process of extracting more than one of these seams is called multiple seam mining. The practice can cause significant geotechnical hazards including pillar and roof instability, in some cases to the point of collapse. While multiple seam mining has been extensively practiced overseas, particularly in the United States and the United Kingdom, due to the differing geological and geotechnical conditions the multiple seam guidelines developed overseas cannot be applied in Australia (Gale, 2004). At this stage, design guidelines do not exist to minimise the geotechnical hazards of multiple seam mining for Australian conditions.

The project aimed to begin the process of establishing multiple seam mining guidelines by utilising the numerical modelling package, LaModel, to understand the occurrence of multiple seam interactions in a study of an underground coal mine in the Bowen Basin, Queensland. The study aimed to quantify the stress impacts during development and extraction of longwall panels in the Argo seam as a result of the overlying bord and pillar and longwall workings in the Castor seam at Cook Colliery. An understanding of the nature of multiple seam interactions will allow mines to identify regions where poor ground conditions are likely and implement procedures, including primary and secondary support plans to mitigate the adverse impacts.

Using LaModel the total vertical stress, multiple seam stress, seam convergence and pillar safety factor were mapped for the thirteen longwall panels of the Castor seam. Modelling found that severe interactions would occur below goaf edges and chain pillars of overlying longwalls, which is in line with the prior research. A region of increased interaction was found below areas of very complex bord and pillar workings where secondary extraction has taken place. The results were used to conduct a risk analysis of the proposed Argo seam longwall panel gate roads to identify regions of low, medium and high risk of adverse ground conditions as a result of multiple seam interactions. It is recommended that in regions of medium and high risk further work should be conducted to plan mitigation methods (e.g. primary and secondary support modifications) for increased vertical stress.

While LaModel provided adequate results for the purpose of this project, the program considers a frictionless laminated overburden therefore does not account for horizontal stress impacts acting on the seam. Furthermore, the pillar safety factors are generated in such a way that they yield unrealistically low results and as such could be relied upon for relative comparison only. The validity of the model was only loosely confirmed by comparison to site experience from only LW201 panel and extensometer or stress data was not available. It is recommended that once mining of the LW202 panel is completed the model be validated from experience and data in the gate roads of this panel and modified accordingly.

Further work on this project could include expanding the project to several multiple seam sites in Australia to establish an Australian database for multiple seam mining interactions and develop multiple seam mining design guidelines for Australian conditions

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1. INTRODUCTION

1.1 BACKGROUND

The Queensland coal mining industry has been in operation since the mid to late 1800's (Whitemore, 1985) and has contributed significantly to both the economy and the development of the state's identity. While coal deposits in Australia commonly exist as multiple seams superimposed upon each other, underground coal mining practices have primarily focused on extracting only the most economical seam (Gale, 2004). However, as current resources are exhausted and technology advances, the possibility of mining additional seams can be considered to account for the increase in demand. Mining of multiple coal seams is widely practiced overseas, particularly in the United Kingdom (UK) and the United States (US), where approximately 70% of the national coal reserves exists in multiple seam situations (Ellenberger et al, 2003). International experience has led to the development of design guidelines for multiple seam mining however due to Australia's differing geological and geotechnical conditions, they are often not applicable (Gale, 2004).

Multiple seam mining can result in severe geotechnical consequences, which arise when seams are located within close proximity to each other. Vertical and horizontal stresses concentrate in pillars and along goaf edges during mining which can result in difficult mining conditions for subsequent seams (Hill, 1994). These concentrations may extend up to four pillar widths above and below remaining pillars (Gale, 2004). Roadways that exist within this increased stress zone are more likely to be affected by deformation and have greater support requirements. Design parameters such as roadway and panel orientations, support requirements and pillar design can affect the impact multiple seam mining has on ground conditions within the seam.

Numerical modelling has advanced to a stage where the modelling of multiple seam stress interactions is possible to an acceptable degree of accuracy. As such, models can be used by mining companies to predict the location and magnitude of any adverse ground conditions and allow for appropriate planning. Computer simulations allow geotechnical and mining engineers to determine magnitude and location of the multiple seam interactions as well as other associated parameters such as roadway safety factors.

This research project is concerned with the multiple seam mining operations at Cook Colliery near Blackwater in Central Queensland. The colliery is situated within the Bowen Basin with three major coal seams identified on the lease. The middle Castor seam was extensively mined over approximately a thirty-year period using both bord and pillar and longwall methods. The Colliery has recently ceased mining in the Castor seam and has begun development and operations of a longwall in the lower Argo seam.

1.2 PROBLEM DEFINITION

At Cook Colliery, the Argo seam is situated within 230m to 260m below the surface and approximately 14m – 24m below the sealed Castor seam. The longwall panels that are planned for the Argo seam will be developed below both bord and pillar and longwall workings. Unexpectedly high stress concentrations such as those beneath isolated pillars and goaf edges can cause deformation and, if not adequately supported, failure of roadways and pillars. Previous attempts to develop headings below Castor longwall goaf zones have resulted in extremely difficult mining conditions and abandonment of the drives (Plowman, 2012) While some brief studies have been conducted, no information currently exists outlining the impact of the concentrated stresses beneath Castor pillar and goaf edges on the current and proposed Argo seam workings. As such, the magnitude of the stresses and their locations along proposed development headings are not known and cannot be planned for.

1.3 AIMS AND OBJECTIVES

This research project aims to quantify the stress induced during development and extraction of the Argo seam as a result of the overlying bord and pillar and longwall workings in the Castor seam at Cook Colliery.

To support this aim, the following objectives have been defined:

- Evaluation of geological and geotechnical data in conjunction with analysis of Castor and Argo seam mine plans to develop an appropriate numerical model for the multiple seam interactions at the site;
- Numerical modelling of the stresses induced adjacent to the Argo seam by the remaining Castor workings using an appropriate software package;

- Completion of a thorough analysis of the resultant stress profiles and identification of risk of multiple seam interactions within proposed gate roads; and
- Validation of results through comparison with experience encountered in previously developed roadways.

1.4 SIGNIFICANCE TO INDUSTRY

Numerical modelling of the stress impacts at Cook Colliery will allow the colliery to understand the nature of the stress that they are likely to encounter. Identification of the location and magnitude of the interactions will allow the implementation of measures to mitigate the adverse impacts of the interactions. Examples of mitigation methods include the following:

- Ensuring secondary support is increased and installed in a timely manner to account for the increase in stress;
- Planning of cut throughs and intersections to avoid high risk areas; and
- Modifying maintenance schedules so that no extended delays are encountered during development of high-risk zones.

Within the wider industry, as the likelihood of multiple seam extraction increases, the understanding of stress behaviour becomes vital for assessing the feasibility of proposed operations. If companies are able to numerically model the stresses that will be incurred for proposed developments in the prefeasibility stages, then they may be able to modify mine plans including panel and roadway orientation and pillar design to accommodate. This project aims to create a pathway for more study into multiple seam mining practice in Australia such that Australian design guidelines for multiple seam mining may be achieved.

1.5 SCOPE

The research project will predict the stress conditions of the longwall panels in the Argo seam at Cook Colliery. An appropriate numerical modelling software package will be selected in order to conduct the stress analysis. While the selection of the software will be justified within the report, a comparison of the stress analysis using multiple software options will not be included. The project will identify the current geotechnical characteristics of the mine however details of material properties will be limited by availability of the data. The effects of strata and overburden properties will be used to determine the stress conditions however the effects of groundwater will be deemed negligible for the purpose of this investigation. Only multiple seam interactions within the Argo seam as a result of undermining will be considered for analysis, the impacts of undermining upon the previously mined Castor seam workings will not be considered. However, this is a possible direction for the project to be extended in the future.

1.6 PROJECT MANAGEMENT

A comprehensive project management plan was derived for this project. The plan included a breakdown of tasks, schedule, resource requirements, risk assessment and contingency plan. Details of the plan can be found in Appendix B. Throughout the project, delays were incurred in the modelling process however by use of the contingency plans, the project was able to be completed on time. The project schedule, including expected and actual completion dates is shown in Table 1.

Table 1.
Project Schedule

Task	*Expected Completion Date*	*Actual Completion Date*
Supervisor Consultation	30/10/2016	TBA
Project Proposal	24/03/2016	24/03/2016
Annotated Bibliography	22/04/2016	22/04/2016
Literature Review	16/05/2016	16/05/2016
Progress Report	25/05/2016	25/05/2016
Numerical Modelling	10/09/2016	17/09/2016
Seminar	22/09/2016	22/09/2016
Final Report	10/10/2016	10/10/2016
Preparation of Conference Paper	28/10/2016	28/10/2016
Completion of Thesis Project	07/11/2016	07/11/2016

2. SITE OVERVIEW

2.1 LOCATION

Cook Colliery is located approximately 830km North-West of Brisbane in Central Queensland. At 30km south of the town of Blackwater, the colliery mines coal from the Bowen Basin over two seams. The Cook Colliery site produces both thermal and coking coal at an approximate 20% to 80% ratio. Figure 1 displays the location of the mine in relation to the Upper Permian coal measures of the basin.

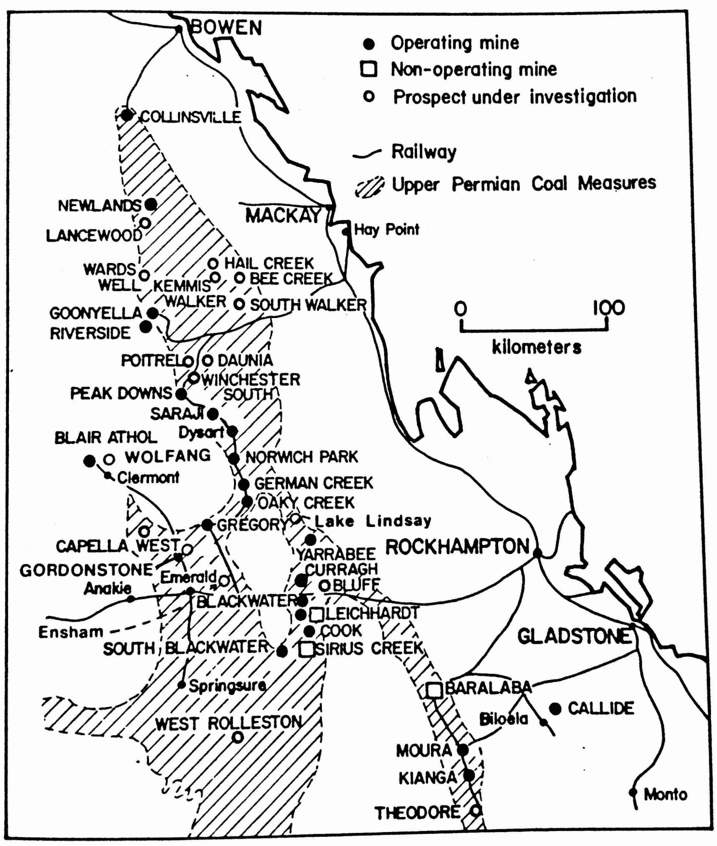


Figure 1. Map of Bowen Basin (Mallet, 1987)

2.2 GEOLOGY

Three coal seams exist within the lease, namely the Aries, Castor and Argo seams in order of their depth from the surface. The Argo seam, which is currently in production, ranges in depth of 230m – 260m below the surface. The seam thickness varies from 4.2m to 4.5m throughout the lease with a gradual dip of 3° towards the South-East. The

Argo seam is situated approximately 14m – 24m below the Castor seam. A typical stratigraphic column from the South-East region of the lease is displayed in Figure 2.

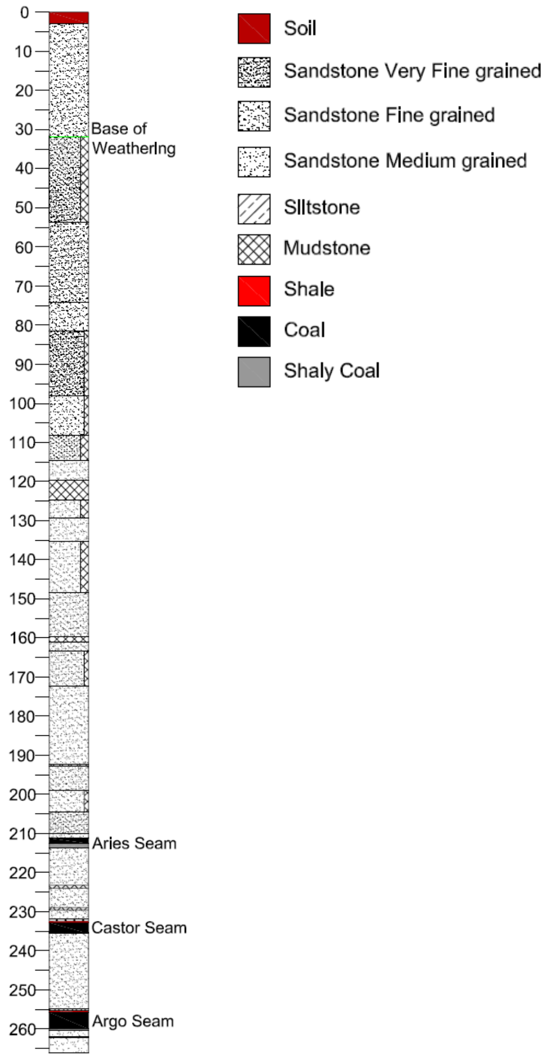


Figure 2. Typical stratigraphic section in the South East of the Cook Colliery lease.

The overburden and interburden of the seams consists mainly of very fine to medium grained sandstones. The immediate roof of both the Castor and Argo seam consists of a thin (<1m) layer of carbonaceous shale with an average uniaxial compressive strength (UCS) of 5MPa. The UCS of the claystone floor of the Argo seam is ranges from 5MPa to 15MPa.

2.3 MINING SEAMS AND LAYOUT

Mining at Cook Colliery has progressed over two seams throughout the life of the mine. The Castor seam was mined over a thirty-year period using both the bord and pillar and longwall mining methods. The Argo seam is situated beneath the Castor and is currently in production via a series of longwall panels. Table 2 outlines the dimensions of the panels for each seam. The layout of both of the seams is available in Appendix 1.

Table 2.

Seam dimensions

Dimension	*Castor Seam*	*Argo Seam*
Heading pillars	29m x 29m	35m wide
Heading roadway width	6m	5.5m
Bord & Pillar pillars	18m x 18m	-
Longwall width	160m - 195m	150m

Determination of the major principal stress has been conducted several times at the site since 1989. The results show that the major horizontal stress is orientated NE/SW at a magnitude of approximately 1.6 times the vertical stress (Plowman, 2012). The vertical stress increases at 2.5MPa per 100m of depth. The highly faulted nature of the lease results in variations of the principal stress specifically around major reverse structures. In order to overcome the horizontal stress, the development headings of the Argo panels are orientated 135° from North. The cleat direction also affects the longwall face and immediate roof stability if the orientation is within 20° of the face orientation. The mean cleat direction of the South Mains headings in the Argo seam was determined to be 54° however can range from 49° to 64° (Plowman, 2012).

High lateral stress was noted beneath Castor seam longwall panels (Plowman, 2012) during early attempts to develop headings within the Argo. Mining to the carbonaceous shale roof resulted in the heading development being aborted.

3. LITERATURE REVIEW

3.1 COAL MINING PRACTICES

3.1.1 Bord and Pillar Mining

Bord and pillar mining is an underground coal mining method during which "rooms" are extracted in the coal with pillars left for roof stability. A simplified bord and pillar design is displayed in Figure 3.

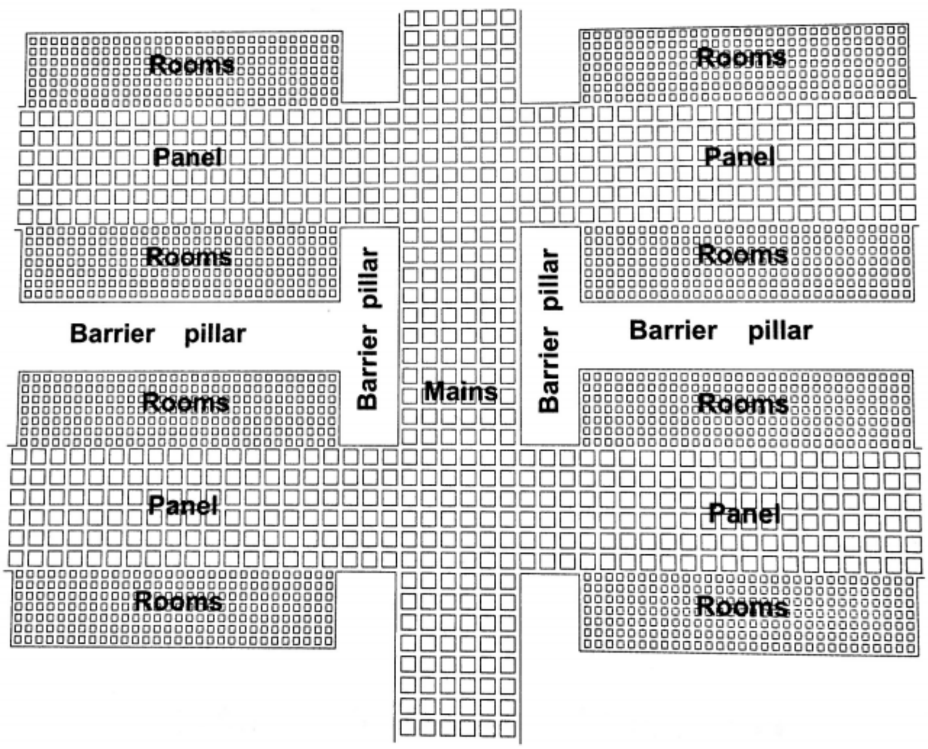


Figure 3. Example bord and pillar layout (Peng, 2008).

A series of headings or mains are driven to provide machinery access and ventilation to the panels. Primary extraction occurs during development of the rooms however secondary extraction of the pillars can occur during retreat from the panel. Barrier pillars are left surrounding the panels in order to contain the overburden load from extracted material and increase geotechnical stability.

3.1.2 Longwall Mining

Longwall mining is an underground coal mining method by which panels of coal are extracted. A typical longwall layout is displayed in Figure 4.

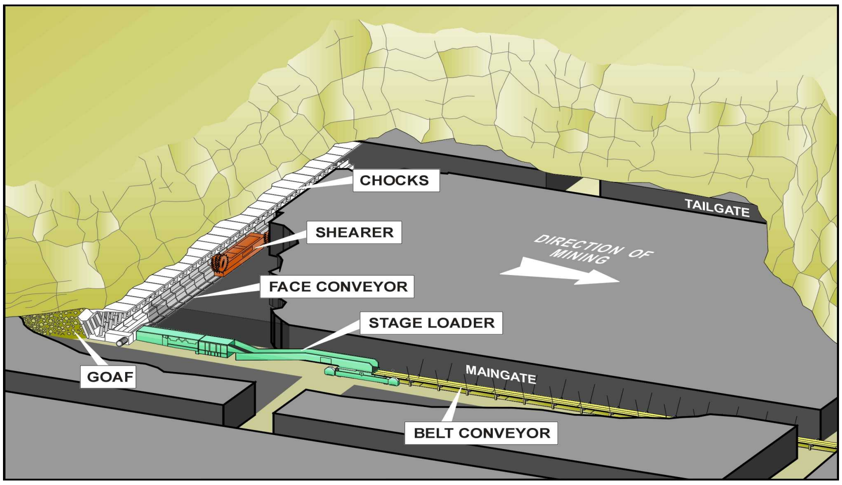


Figure 4. Longwall mining (Kizil, 2014))

Between two and four entry headings are driven to form the gate roads of the panel (Peng, 2008). The main gate drives are used for equipment and personnel transport as well as a belt road for the transportation of coal. The main gate also provides the intake of fresh air to the face. The tail gate drive/s are used for the flow of return air away from the longwall face. Coal is cut from the face by a shearer which is mounted on the panline of an armoured face conveyor (AFC). The roof over the shearer is supported by a series of hydraulic supports called shields or chocks. The shields advance as the shearer progresses through the panel and the immediate roof of the extracted coal seam caves behind the supports. The region of caved material behind the longwall is referred to as the goaf. The longwall caving process is displayed in Figure 5.

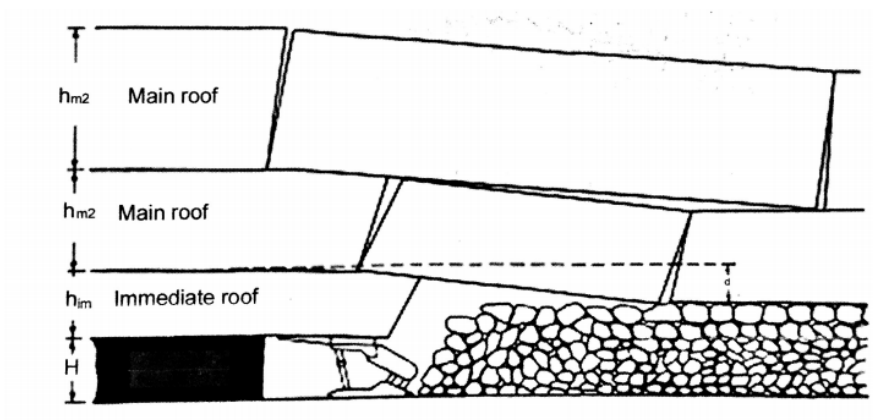


Figure 5. Longwall caving process (Peng, 2008)

The major geotechnical issue surrounding longwall mining is the redistribution of the overburden stress due to the extraction of the seam and the caving of the overburden. Since the goaf cannot transfer the original in situ stress of the intact rock, the stresses are redistributed to the chain pillars surrounding the panels.

3.2 MULTIPLE SEAM MINING

3.2.1 Multiple Seam Principles

Multiple seam coal mining refers to the process where two or more coal seams are mined either simultaneously or subsequently to one another. The process of actively mining the lower seam where the upper seam has previously been extracted is referred to as undermining and is shown in Figure 6.

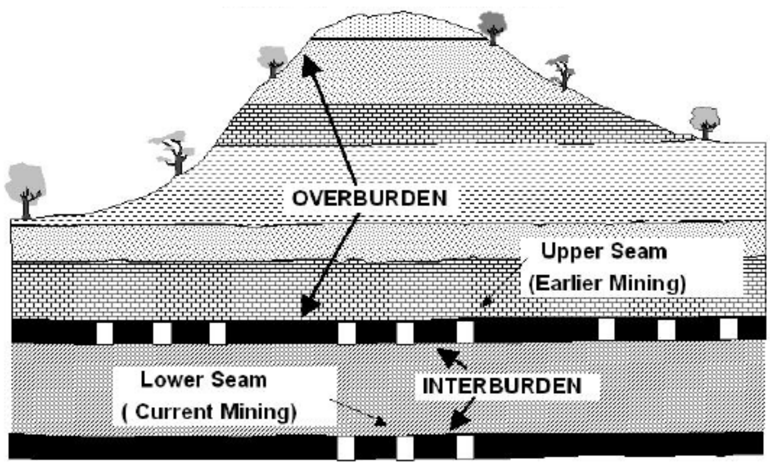


Figure 6. Schematic of an undermining situation (Ellenberger et al, 2003)

Overmining (shown in Figure 7) is the process of mining the upper seam once mining of the lower seam is completed. Overmining presents different multiple seam interactions to undermining including subsidence, arching/caving and vertical load transfer (Zhou, 1991). Since Cook Colliery is an undermining operation, interactions specific to overmining will not be further investigated within this report.

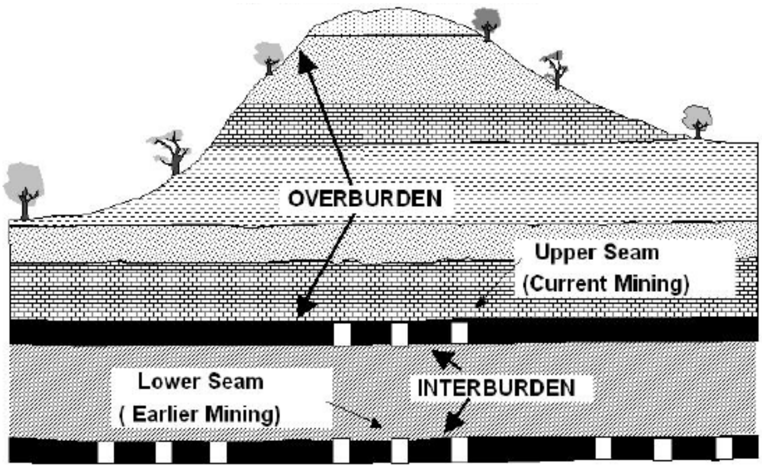


Figure 7. Schematic of an overmining situation (Ellenberger et al, 2003)

Multiple seam mining has occurred previously for both longwall and bord and pillar mining methods with longwall mining generally producing the most adverse mining conditions for undermining.

3.2.2 Multiple Seam Mining Interaction

Adverse ground conditions caused by multiple seam mining activities are referred to as multiple seam interactions. Multiple seam interactions are produced due to the redistribution of stress where coal has been extracted. The weight of the overburden is transferred from relatively uniform loading to concentrated areas such as goaf edges, barrier pillars and isolated remnant pillars (Ellenberger et al, 2003). Zipf (2005) identifies the main factors controlling the mechanics of interactions to be the vertical and horizontal stress concentrations, stress re-direction and bedding plane slip bands.

Since load cannot be transferred through voids created by excavations, the in-situ stresses are greatly altered during mining. The additional load is referred to as the abutment load (Suchowerska et al, 2013) and must be considered for the prediction of multiple seam analyses. The stress redistribution is greater when longwall mining has occurred in the upper seam than for bord and pillar mining due to the larger excavation size. Multiple theories exist surrounding the characteristics of stress redistribution considering either the pillars or the mine excavation to be the major structural element. The pressure bulb theory presented in both Chekan, Matetic and Galek (1988) and Xinjie, Xiaomeng and Weidong (2016) assumes that the vertical stress concentrates within the remaining pillars with the increase in stress above and below the pillars distributed in a “bulb” fashion as displayed in Figure 8.

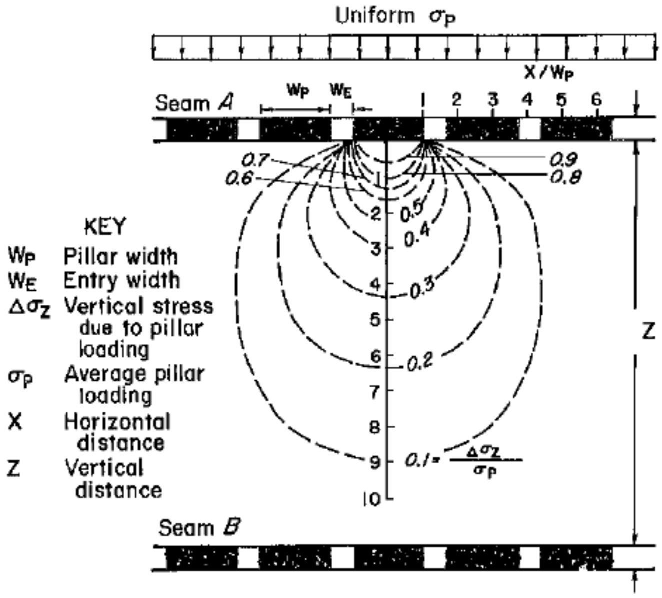


Figure 8. Pressure bulb theory (Chekan, Matetic and Galek, 1988)

This theory identifies a zone of increased vertical stress that extends up to four times the pillar width above and below the pillars at which point it decreases to zero influence (Gale, 2004). Interburden stratigraphy affects the development of pressure bulbs with high competency materials (e.g. sandstones) inhibiting development and weaker materials (e.g. shales) increasing the influence of the overlying pillars (Chekan et al, 1988). The typical load angle, which describes the geometry of overburden distributed onto the pillars and goaf, was identified to be between 20 and 30 degrees (Gale, 2004). As each pillar exhibits pressure bulbs, the stress concentration at a given point is the combination of the overlapping pressure from neighbouring and overlying/underlying pillars. In multiple seam mining, adverse ground conditions are evident when the pressure bulbs from overlying pillars interact with the lower seam. Chekan et al (1988) identify that the pressure bulb theory is most useful in analysing pillar load transfer when passive loading is considered.

The pressure arch theory (Suchowerska et al, 2013; Chekan and Matetic, 1988) considers the stress as a redistribution around mine openings and goaf areas rather than through pillars. The theory suggests that a pressure arch forms around the opening during excavation as shown in Figure 9 creating a zone of stress relief.

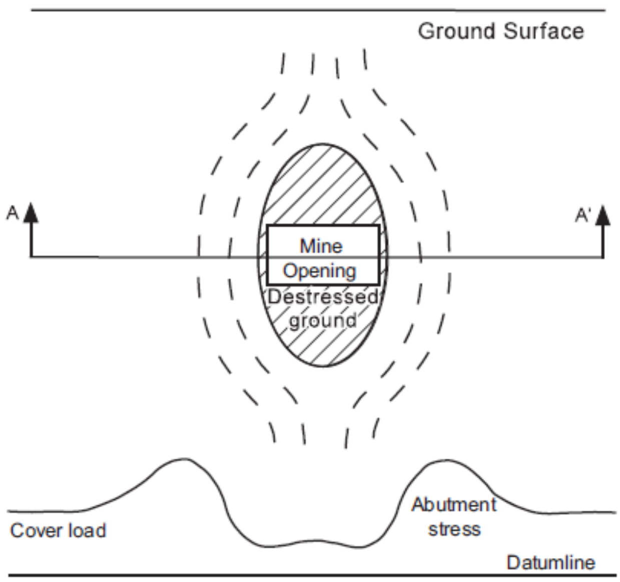


Figure 9. Pressure arch theory (Suchowerska, et al, 2013)

The vertical stress is redistributed via the pressure arch imposing increased stress on the adjacent pillars. The magnitude of the abutment pressure and the geometry of the arch are dependent on the depth, opening width and material properties of the strata. In multiple seam situations, the abutment stresses incurred by the pillar are transferred vertically to overlying and underlying strata and onto workings in adjacent seams should the seams be in close enough proximity. On the other hand, in close distance coal seams, the de-stressed zone could also be applied to adjacent workings reducing the overall vertical and horizontal stress. The de-stressed zone is particularly evident below longwall goaf areas (Chekan and Matetic, 1988).

In general, the stress concentrations surrounding longwall goaf zones are assumed to be greatest at the edge of the goaf and dissipate to the original stress state as the lateral distance from the goaf increases. On the other hand, it is widely agreed that the concentration of stress within pillars is distributed across the pillar such that the centre of the pillar carries the greatest load. Figure 10 graphically summarises the abutment stress at goaf edges and across pillars. The figure also defines the maximum width allowable for the structure to be considered a major isolated structure as theorised by Mark, Chase and Pappas (2007).

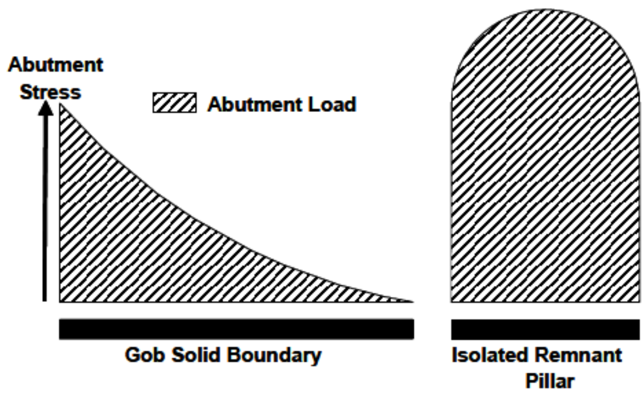


Figure 10. Goaf and pillar abutment stress (Mark et al, 2007).

The parameters that determine the severity of adverse interactions defined by Chekan and Matetic (1988) as being classified into one of two categories; fixed or design parameters. Fixed parameters are those that cannot be altered, including the geological environment, in situ stress, depth of cover, interburden thickness, overburden strata material properties and the strength of the coal. Design parameters are those engineering parameters which can be altered to optimise mining conditions, including pillar size, span of entries, mining method, mining height and sequencing. This strongly aligns with the studies conducted by Zipf (2005) and Chase, Worley and Mark (2005) both of which also identify the rock quality of the overburden and interburden and the angle of draw as major influencing parameters.

3.2.3 Experience from Multiple Seam Operations

Previous experience, specifically from overseas multiple seam operations, has identified that the nature of multiple seam interactions differs between sites due to variance in geological and geotechnical conditions.

Multiple seam operations in the United States (US) are likely to have been bord and pillar operations in earlier seams and longwall operations in more recent seams. The existence of up to 25 coal seams in a given stratigraphic section in some regions of the US leads to many operators mining above or below current and abandoned workings (Zhou, 1991). As such, adverse ground conditions are of major concern. Mark et al (2007) conducted a study assessing the success of over 344 cases of multiple seam workings in 36 mines within the US. The study found a strong correlation between the interburden width and ground conditions noting that as the interburden distance between the seam increases, so too does the mining conditions for undermining.

Chekan et al (1989) identified significant ground control issues, including pillar instability, roof shearing and floor heave in a study of a mine operating in the lower Banner coalbed in Dickenson County, VA. The longwall operation was developed approximately 35m below abandoned workings in the Upper Banner coalbed. The Lower Banner workings suffered some adverse effects due to subsidence from partial bord and pillar workings in the subjacent Tiller coalbed (approximately 220m below) however this was deemed to have less influence on the ground conditions than the Upper Banner workings (Chekan et al, 1989).

Minimal data from Australian multiple seam operations is available as the practice has been significantly less popular than single seam mining. Gale (2004) conducted a study investigating the multiple seam interactions where subsequent seams were mined by longwalls for a limited number of collieries in central NSW. Difficult ground conditions occurred during longwall mining of the lower seams at the Kemira and Wyee operations in New South Wales. At both of these collieries the upper seam had been mined by bord and pillar mining and the interburden thickness ranged from 20m – 35m (Gale, 2004). Similarly, significant deformation of gateroads occurred in the lower seam of the Pacific and Stockton Borehole collieries in the Newcastle Coalfield where both upper and lower seams were mined using longwall methods. Both the Pacific and Stockton Collieries had interburden distances of less than 40m and the panels of both seams were oriented in the same direction (Gale, 2004).

The development roadway behaviour was investigated by Gale (2004) for the Glen Munro coal seam which was being developed 30m-40m below the Blakefield seam at Beltana Mine in the Hunter Valley, NSW. The study highlighted multiple issues with the conditions of the roof, ribs and floor when undermining different components of the Blakefield seam. The results, shown in Figure 11, identified significant deformation particularly under pillar edges and in cut-throughs below pillars.

Location	Stresses			Roadway Deformation		
	Vertical	Horizontal	Shear	Floor	Ribs	Roof
Virgin	8.25MPa	Tectonic Strain 0.7	-	Minor heave failure to 1.5m	Yield 2-3m	Bedding shear to 2m
Under Goaf (Bedding plane shear fractures pre-existing)	-	-	0.5MPa	Minor heave failure to 1.5m	Yield 2-3m	Bedding shear to 2m
Indented from Goaf Edge	*1.15	-	3MPa	Heave failure to 2-3m	Yield 4-5m	Bedding shear to 2m
Indented from Pillar Edge	*1.5	-	4.5MPa	Major heave failure to 4m	Yield 5-6m	Biased gutter shear to 3m+
Under Pillar (cut-through)	*1.6	*1.3	0.5MPa	Major heave failure to 3m	Yield 5-6m	Bedding shear to 3m

Figure 11. Multiple seam development roadway behaviour (Gale, 2004)

The results indicate that at this particular site the elevated shear stress conditions associated with pillars and goaf edges can induce significant bedding shear and floor and rib deformation (Gale, 2004).

The study also compared Australian conditions with previous experience from British Coal operations in the United Kingdom (UK) where multiple seam mining is a more common practice. Mining in the UK is primarily focused on advance and retreat longwall methods in both seams. The most common interactions observed from fourteen sites are as follows:

- Roof softening (of up to 4m);
- Significant floor heave;
- Displacement of maximum 100mm in the roof;
- Panel abandonment due to roadway deterioration during drivage; and
- Some significant (up to 3m) roof cavities.

Experience from the UK also saw a correlation between the interburden distance and the severity of the interactions with interburden distances of less than 100m displaying substantial to major interactions resulting in poor to very poor ground conditions. Due to differences in Australian geological conditions, Gale (2004) determined that the multiple seam design guidelines that are followed in the UK or the US cannot be applied.

3.3 NUMERICAL MODELLING PRINCIPLES

3.3.1 Numerical Modelling Principles

The prediction of multiple seam interactions is integral for planning and design of underground coal operations. Numerical models have proved to be successful in determining the response of rock masses to mining activities in a number of mining and ground control applications. Numerous forms of numerical modelling techniques exist with the most popular methods for modelling rock mechanics problems as follows (Jing, 2003):

- Finite Element Modelling (FEM);
- Boundary Element Modelling (BEM);
- Discrete Element Modelling (DEM);
- Finite Difference Modelling (FDM); and
- Hybrid combinations of the above techniques.

FDM obtains approximate solutions to partial differential equations (PDEs) by the replacement of partial derivatives of the objective function (for example, displacement) over a regular grid of nodes such as those displayed in Figure 12 (Wheel, 1996).

The standard five point difference scheme for FDM means that the resultant equation at grid node (i,j) is a combination of the function values of the surrounding four nodes (Figure 12). Finite volume modelling (FVM) is a type of FDM commonly used in stress analysis applications. FVM overcomes the limitations of inflexible grids of FDM with unstructured grids of arbitrary shape (Jing, 2003).

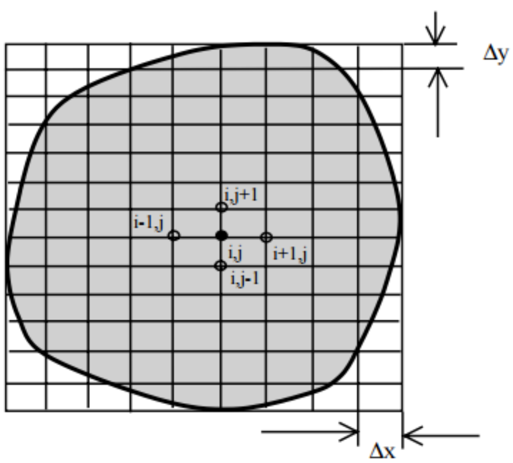


Figure 12. Regular quadrilateral grid for FDM (Jing, 2003)

DEM is a discontinuum method which represents the rockmass as an assemblage of distinct interacting blocks (Chen, 2016). The method has the capability to model scale-dependent material states during failure and large-scale deformations through simplified interaction mechanics (Johnson, 2011). While DEM can capture complex behaviour of material through separately acting physical algorithms, the process is computationally expensive and the availability of data to define grain properties and contact mechanics is complex (Johnson, 2011).

The popularity of FEM can be attributed to its flexibility in modelling complex geometries and boundary conditions as well as material inhomogeneity. Three main phases exist in the FEM process; these include the mesh and discretisation of problem domain, the approximation of the PDE's at each element and the assemblage of individual elemental equations into a global system of equations by which the final solution to the problem is determined (Jing, 2003).

FEM, DEM and FDM discretise the entire body during the modelling process often requiring extensive storage and memory handling capabilities of the computer. As such these methods are often time consuming and expensive. Due to the lower storage and memory handling requirements, BEM is often a more cost and time effective approach to modelling complex geotechnical problems.

3.4 LaModel

3.4.1 Program Overview

LaModel is a displacement-discontinuity (DD), BEM approach developed to analyse the displacement and stresses in flat lying, tabular orebodies such as coal. The program was developed by Heasley (1998) in response to the lack of reliable models for multiple seam interaction and subsidence prediction in the US. The DD method considers the coal seam as a discontinuity within the displacement of the mine area. As such only the coal seam is discretised. While this may seem to be limiting, in many applications, such as is true for this project, only the stress and displacements acting within and upon the coal seam are of interest. Furthermore, LaModel can more easily compute problems involving large excavations than models such as FEM and DEM which discretise the entire mine area (Heasley, 1998). This is particularly advantageous for modelling of longwall excavations.

In addition to the features stated above, the LaModel program has the following capabilities (Heasley, 2010)

In addition to the features stated above, the LaModel program has a number of capabilities which allow for accurate analysis. The program can be used to model the multiple seam interactions for up to four coal seams and allow for multiple in seam materials to be defined. Multiple excavation steps can be defined within the model so that the development of abutment stresses can be considered.

3.4.2 Laminated Overburden

The program is used to model both singular and multiple seam stresses as well as subsidence. LaModel is particularly advantageous for this project as it considers a laminated overburden, such is the case with most coal deposits including Cook Colliery. By applying a laminated overburden, the overburden strata are considered to be a number of beds of equal width that slide over each other along frictionless surfaces (Heasley and Chekan, 1999). For this reason, LaModel does not calculate shear stress or displacement within multiple seam operations.

3.4.3 Pillar Strength Formula

In order to produce realistic results, the strength of the coal pillars is defined in LaModel from empirical methods, in particular, the Mark-Bieniawski pillar strength formula. The formula was derived from the extensive databases used to create the 'Analysis of Longwall Pillar Stability' (ALPS) and the 'Analysis of Retreat Mining Pillar Stability' (ARMPS) programs in the US. The Mark-Bieniawski pillar strength formula is outlined in Equation 1:

$$S_p = S_i\left[0.64 + 0.54\left(\frac{w}{h}\right) - 0.18\left(\frac{w^2}{L\times h}\right)\right] \qquad 1)$$

Where:

S_P = Pillar strength (psi);

S_i = In situ coal strength (psi);

W = Pillar width (ft);

L = Pillar length (ft); and

h = Pillar height.

As the LaModel program was developed in the US the imperial system of psi, ft is used rather than the metric MPa, m.

The model also assumes a stress gradient from the pillar rib which is detailed by Equation 2:

$$\sigma_P(x) = S_i\left(0.64 + 2.16\left(\frac{x}{h}\right)\right) \qquad 2)$$

Where:

$\sigma_P(x)$ = Peak coal stress (psi);

x = Distance into pillar (ft);

S_i = In situ coal strength (psi); and

h = Pillar height.

The effect of this assumption means that the load carrying capability of the pillar varies toward the centre of the pillar, with the load bearing capacity at the core of the pillar being the greatest.

4. MODEL SET UP

4.1 CASE STUDY DETAILS

Cook Colliery has extensively mined the Castor seam and is currently in production of the second longwall (LW) panel in the Argo seam. The details of mining in each seam are detailed in Table 3 below.

Table 3.
Mining Details for Cook Colliery

	Castor Seam	*Argo Seam*
Mining method	Bord & Pillar, Longwall	Longwall
Depth of cover	180 - 210m	230 - 260m
Seam thickness	2.4 – 2.9m	4.2-4.5m

Multiple series of LW extraction are planned for the Argo seam however for the purpose of this study only the southern panels LW201-LW215 will be investigated. The area of interest for this study is outlined in Figure 13.

The Castor seam contains bord and pillar workings of variable size and two LW sections. The two southern panels have a face width of 205m while the four eastern panels have a face width of 193m. All roadways are 5m wide. The Argo LW panels have a face width of 180m and roadway width of 5m. It is important to note that the Argo LW panels are not in the same orientation as the Castor LW panels as is the case for studies outlined in the literature review.

As discussed in Chapter3, the overburden to interburden ratio and the interburden material properties were defined as critical parameters influencing the magnitude and propagation of multiple seam interactions. The overburden to interburden ratio ranges from 9.6 to 18.5 increasing towards the South-East of the lease. Some multiple seam interactions are expected across the entire lease with severe interactions expected in regions where the overburden to interburden ratio is greater than 16.

The interburden between the Castor and Argo seams consists of fine to medium grained sandstone with shale forming the immediate roof of the Argo seam. Literature research determined that massive materials such as sandstone can inhibit the abutment loads and limit the extent of pressure bulb development.

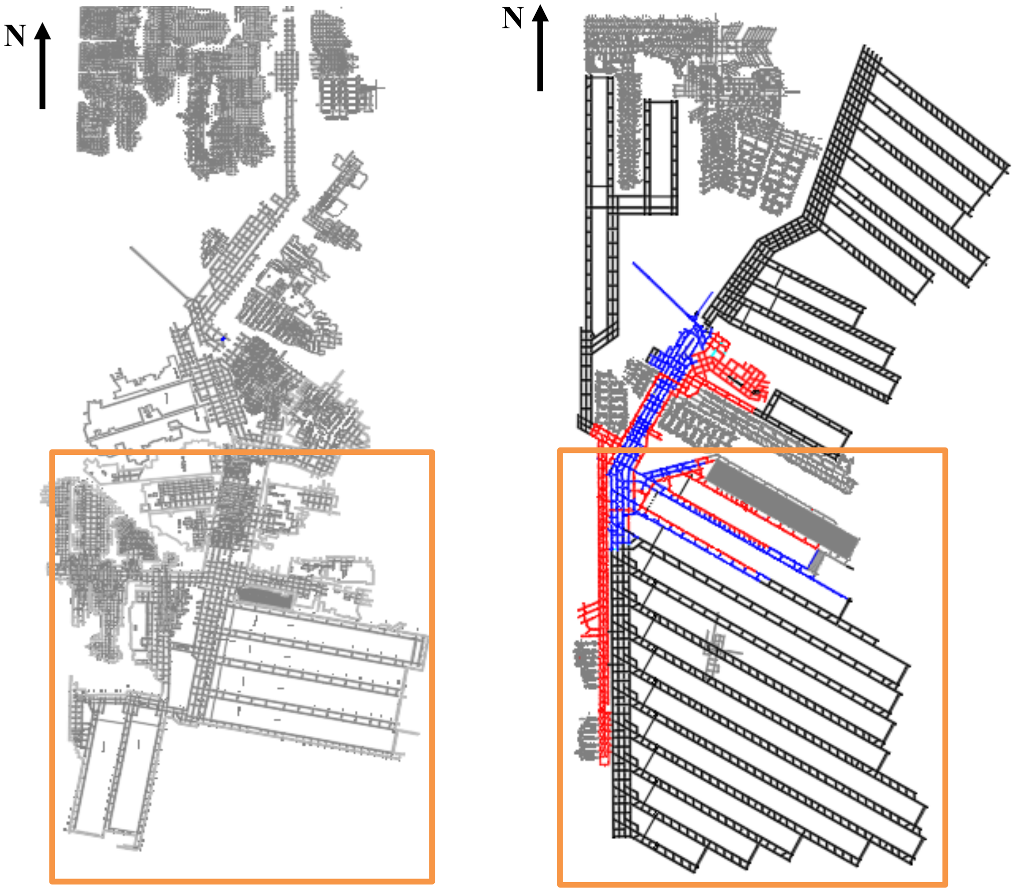


Figure 13. Area of Study for Castor seam (left) and Argo seam (right).

4.2 Model Input Parameters

4.2.1 Geometry

A key feature of the LaModel program is the ability to generate the model grid directly from the mine plans within the AutoCAD program (Heasely and Agioutantis, 2007). A grid of identical dimension and origin is generated using the LaModel 'stability mapping' application for each seam. The Argo and Castor mine plans were rotated such that the Argo longwall panels were horizontal in order to simplify grid generation. Grids and modelling was conducted on a panel by panel basis. Each grid element is allocated a property depending on whether it is solid coal, roadway or goaf. An example of the grid generated for a LW210 for both the Castor and Argo seams is shown in Figure 14.

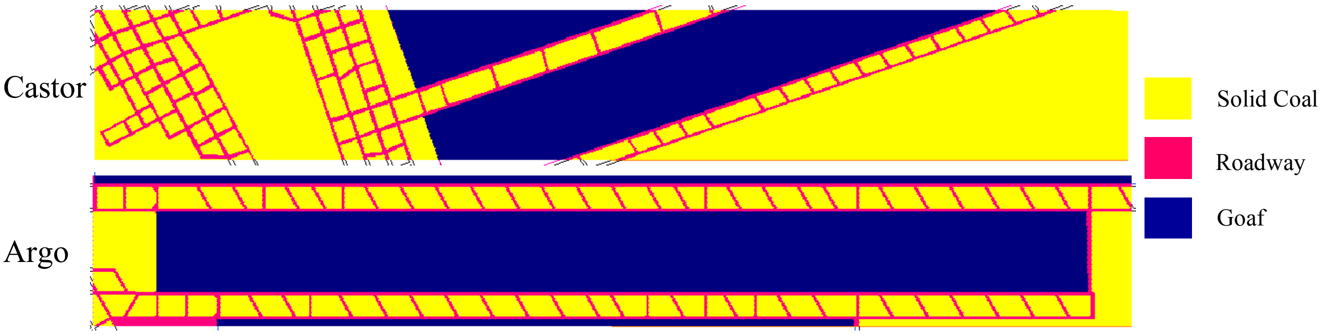


Figure 14. Seam grids for Castor (top) and Argo (bottom) generated in AutoCAD.

4.2.2 Grid Boundary

The properties of the grid boundary determine how the model acts towards the edge of the grid. Two boundary conditions exist in LaModel and can be applied to any of the four sides of the grid. A rigid boundary assumes an unyielding boundary such that no displacement occurs outside of the grid (Heasley, 1998). A symmetric boundary assumes the slope of the displacement at the model boundary is zero (Heasley, 1998). A symmetric boundary condition was applied to all sides of the grid as this provides a considerably more realistic boundary response than a rigid model for extensive modelling areas such as longwall panels (Heasley, 1998)

4.2.3 Grid Size

The model domain is constrained to a 1000 x 1000 element grid. While the element size is unconstrained it was identified to be a critical parameter influencing the accuracy of the model. Smaller element sizes ultimately yield a more accurate model. A sensitivity analysis was conducted in order to determine the optimal element size for the purpose of the model. A small region of the Argo mains was chosen to conduct the analysis such that there was no interference from key features in either seam (e.g. goaf edges, remnant pillars). The total vertical stress of the Argo seam for the selected region (shown in Figure 15) was determined for 1m, 2m, 5m and 10m square elements.

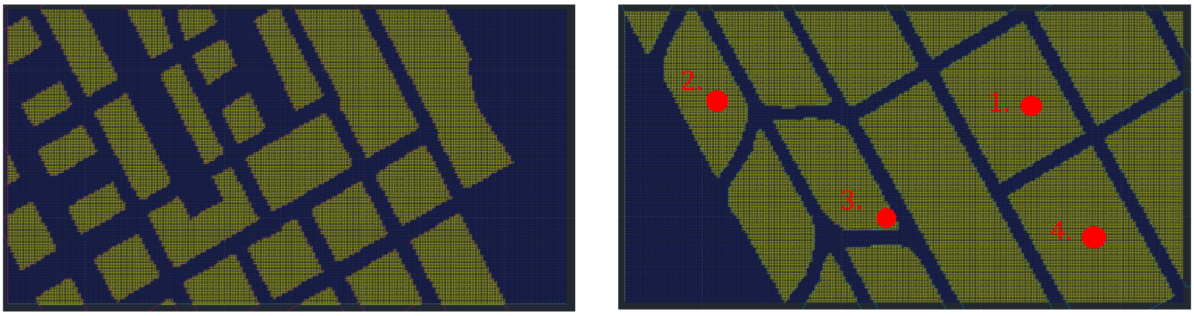


Figure 15. 1m grid of Castor (left) and Argo (right) seams with points of interest identified in Argo seam.

The change in vertical stress at selected points for each grid was analysed with the results outlined in Figure **16**. As is visible, the total vertical stress converges between 1m and 2m element size and the change in total vertical stress for points between 1m and 2m element size is very small. As many panels exceed 1000m in length, in order to analyse each panel as only one model, an element size of 2m was chosen.

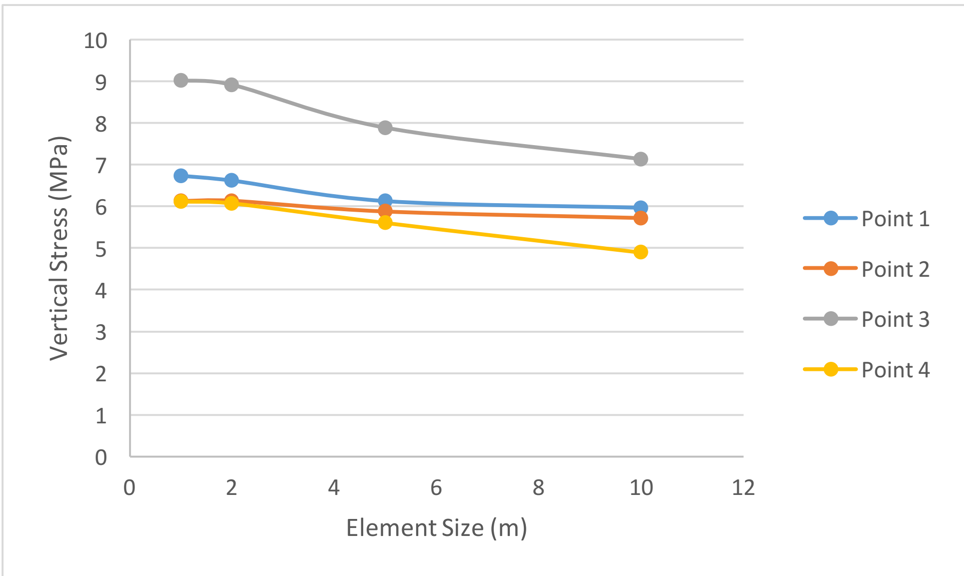


Figure 16. Total vertical stress at points of interest for changing grid sizes.

A sensitivity analysis was also conducted to determine whether the magnitude of the domain would influence the accuracy of the model. Utilising a 2m element size, the total vertical stress was determined over 20 000m^2, 33 600m^2, 41 600m^2 and 50 400m^2 domains. The results were plotted for the same points of interest and are outlined in Figure 17. The size of the domain has little effect on the accuracy of the model.

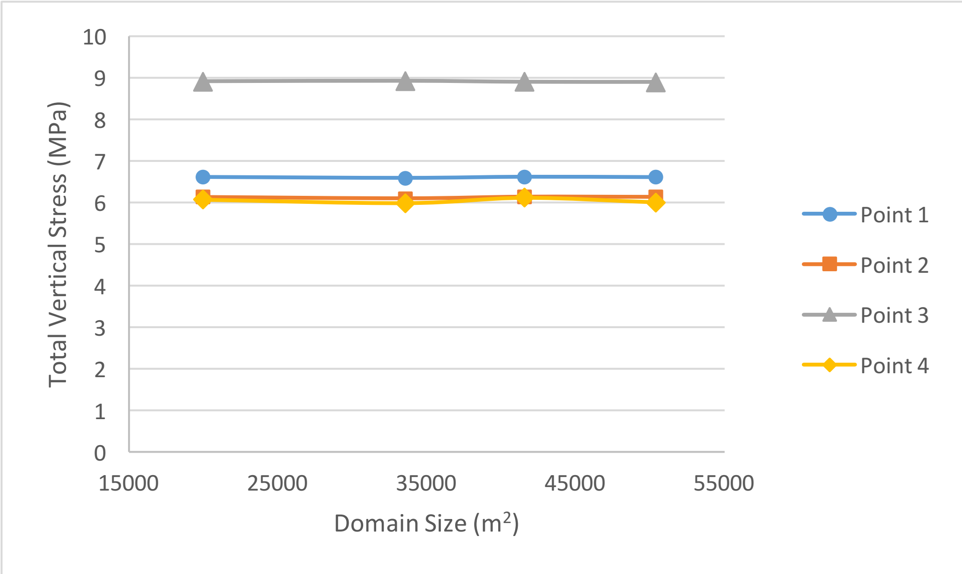


Figure 17. Total vertical stress at points of interest for changing domain sizes.

4.2.4 Coal Parameters

The Mark-Bieniawski coal pillar formula (detailed in Chapter 3) is used to determine the strength of the coal over the pillar. The formula is based on user-defined intact coal parameters. An elastic-plastic relationship was used for the coal assuming a coal strength of 6.205MPa (Lines, 2016) and an elastic modulus of 2.068GPa (Lines, 2016).

4.2.5 Goaf Parameters

The goaf parameters are critical in optimising the accuracy of the model. The amount of load that the goaf can transfer is directly related to the abutment stress applied to the surrounding pillars. LaModel defines the amount of stress the goaf can transfer as a percentage of the in situ stress. Three different goaf materials were defined in the model as follows:

- Castor southern longwall panels;
- Castor eastern longwall panels; and
- Argo longwall panels.

The amount of vertical stress the longwall goaf can transfer is shown in equation 1:

$$\sigma_{1G} = 0.5 - 1.0 \times \sigma_1$$

Where:

σ_{1G} = the vertical stress transmitted by the longwall goaf; and

σ_1 = the total vertical stress.

LaModel provides suggestions for goaf load parameters based on the depth of cover and width of the goaf regions. While Heasley (2010) defines the longwall goaf parameters as critical to the model, a sensitivity analysis established that the change in stress due to depth on chain pillars of three longwall panels converged for σ_{1G} = 0.5-0.7σ_1. As such the longwall panels within the Argo seam were modelled considering a stress transfer of 60% of the in situ stress. Due to the length of time that has passed since the Castor longwall panels were extracted it is reasonable to assume that the caved material has consolidated to a greater extent than the Argo panels. As such a goaf stress transfer capability of 70% of the stress was assumed.

4.2.6 Field Stress & Overburden Parameters

The vertical stress of the site increases at a rate of 2.54MPa per 100m of depth (Lines, 2016) which is input into LaModel as 0.0254MPa/m.

Karabin and Evanto (1999) recommend that the overburden elastic modulus be a thickness weighted average of the elastic modulus of the overburden layers. As detailed in Chapter 3, the major units within the site overburden are fine to medium grained sandstone. The minimal amount of interbedded mudstone and siltstone indicates that the effect of these layers are negligible in comparison to the sandstone layers. As such, the elastic modulus of the overburden was assumed to be equal to that the of the sandstone, 20.7GPa (Lines, 2016). For this reason, a Poisson's ratio of 0.27 (Lines, 2016) was also used.

4.2.7 Lamination Thickness

The lamination thickness in LaModel is a primary factor contributing to the stiffness of the overburden rock mass. An increased lamination thickness will result in an increased stiffness. The stiffness effects the behaviour of the model in a number of ways (Heasley. 2010). As the stiffness of the overburden increases the extent of the abutment zone also increases. Furthermore, a stiffer model smooths the multiple seam stress concentrations over the model domain. On the other hand, as the stiffness decreases the seam convergence and stress above the goaf increase.

LaModel utilises a 'Wizard' to provide a suggestion for the lamination thickness which is determined from Equation 3 (Heasley, 2010):

$$t = \frac{2\,E_S\sqrt{12(1-\upsilon^2)}}{E \times h} \times \left(\frac{5\sqrt{H}-d}{\ln(1-n)}\right)^2 \quad 3)$$

Where:

E = the elastic modulus of the overburden (psi);

υ = the Poisson's Ratio of the overburden;

E_s = the elastic modulus of the seam (psi);

h = the seam thickness (ft);

n = percentage of abutment load (%);

d = the extent of the coal yielding at the edge of the goaf (ft); and

H = the seam depth (ft).

The parameter which cannot be easily determined within the equation is "d", the extent of the yield zone at the abutment edge. The suggested laminated thickness assumes a linear-elastic relationship, therefore d=0. Under this assumption the lamination thickness is 49.79m. However, in reality this is not the case and some distance of coal yielding occurs at the edge of the panel (Heasley, 2010). For a strain softening relationship, LaModel suggests d=19.52m. As this parameter is unknown for the site, the suggested value was utilised. Under this assumption the laminated thickness, which was utilised for the project, is 13.03m.

4.3 MODEL OUTPUT PARAMETERS

Four main outputs were retrieved from the LaModel program in order to establish the occurrence and impact of multiple seam interactions. These are as follows:

- Multiple seam stress (MSS);
- Total vertical stress (TVS);
- Seam Convergence; and
- Pillar safety factor.

MSS is the stress induced upon the active seam due to the mining of the upper seam only (Heasley, 2009). MSS concentrations can exhibit a very irregular pattern across the lease area in accordance with the upper seam mine plan. This is due to the fact that increased MSS is expected below chain pillars and isolated pillars of the Castor seam workings.

TVS is a combination of both the MSS and the overburden stress (Heasley, 2009). TVS also takes the abutment stress from the in seam goaf regions into account. As such, the TVS applied to chain pillars in the gate roads of the Argo seam will change as the longwall retreats. In order to allow for this, the modelling was conducted in stages of panel excavation.

Seam convergence is the displacement between seams as a result of mining in the upper seam (Heasley, 2009). The overburden caving nature of the longwall mining method has a direct impact upon the seam convergence. For any particular point along the gateroads of the panel, the seam convergence increases as the longwall panel retreats past the point.

The safety factor of the pillars is determined by averaging the safety factor of each element within the pillar. The Mark-Bieniawski coal pillar formula is used with an in-situ coal strength of 6.205MPa to determine the peak strength of each element. This is then compared to the stress applied to each element to give the elemental safety factor. This method of determining the pillar safety factor gives a conservatively low safety factor as pillars may not have failed through the core of the pillar however may still have a safety factor less than 1.0 due to failing elements towards the edge of the pillar (Heasley, 2009).

5. RESULTS AND ANALYSIS

The analysis process is detailed in this chapter for one panel with the combined results for all panels detailed separately.

As discussed in Chapter 4 the multiple seam interactions were assessed according to four criteria:

- Total Vertical Stress;
- Multiple Seam Stress;
- Seam Convergence; and
- Pillar Safety Factor.

These criteria were specifically analysed across a number of points of interest (POI) along each of the thirteen panels such as:

- A standard pillar (which was used as a base point for the purpose of comparison);
- Beneath a Castor goaf edge;
- Beneath a Castor chain pillar; and
- Beneath a Castor remnant pillar.

The points of interest selected were distributed over the main and tailgates of each panel as they are subject to different loading due to prior extraction of preceding panels.

The parameters were analysed over four stages to account for the change in stress due to abutment from the retreating longwall. These stages are:

- Stage 1 (Development) – after the development of the gateroads prior to productions of the longwall;
- Stage 2 (Production) – after one third of the panel has been extracted;
- Stage 3 (Production) – after two thirds of the panel has been extracted;
- Stage 4 (Completion) – after full extraction of the panel.

5.1 LW210 Panel

LW210 Panel was chosen as the example panel to detail the analysis process. The mine geometry of the modelled region is shown in Figure 18.

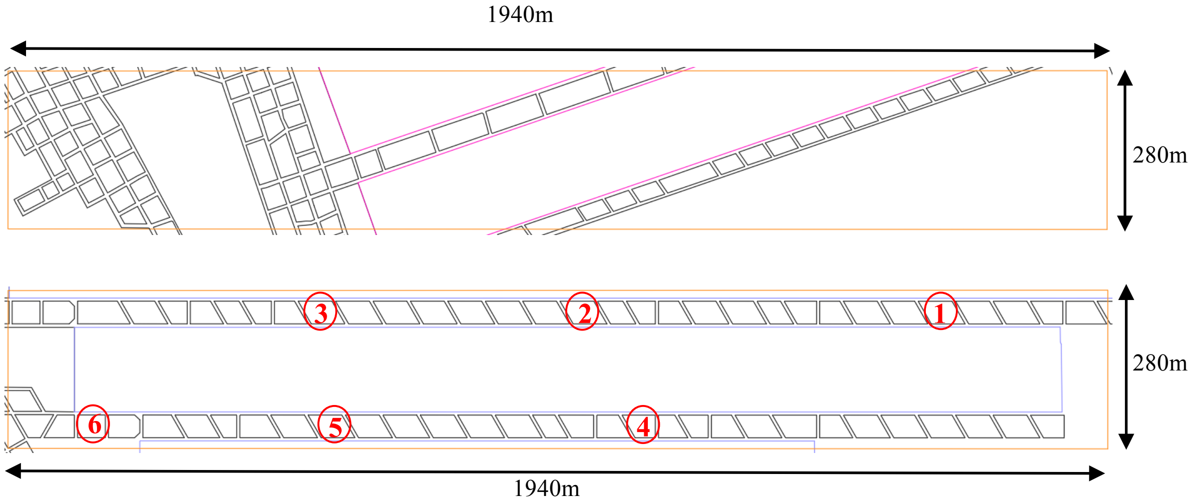


Figure 18. Geometry of the Castor (top) and Argo (bottom) seam areas modelled for LW210 with points of interest identified.

The points of interest are outlined in Table 4.

Table 4.

Points of interest for LW210

Point	*Location*	*Characteristic*
1	Tailgate	Beneath chain pillar with solid coal on one side.
2	Tailgate	Beneath chain pillar with longwall goaf on both sides.
3	Tailgate	Beneath the edge of longwall goaf region.
4	Maingate	Beneath chain pillar with solid coal on one side.
5	Maingate	Beneath the edge of longwall goaf region.
6	Maingate	Base point

5.1.1 Total Vertical Stress

The total vertical stress is the combination of the overburden load, multiple seam stress and the abutment load. The contour plot of total vertical stress developed in LaModel are shown in Figure 19 for each stage of extraction.

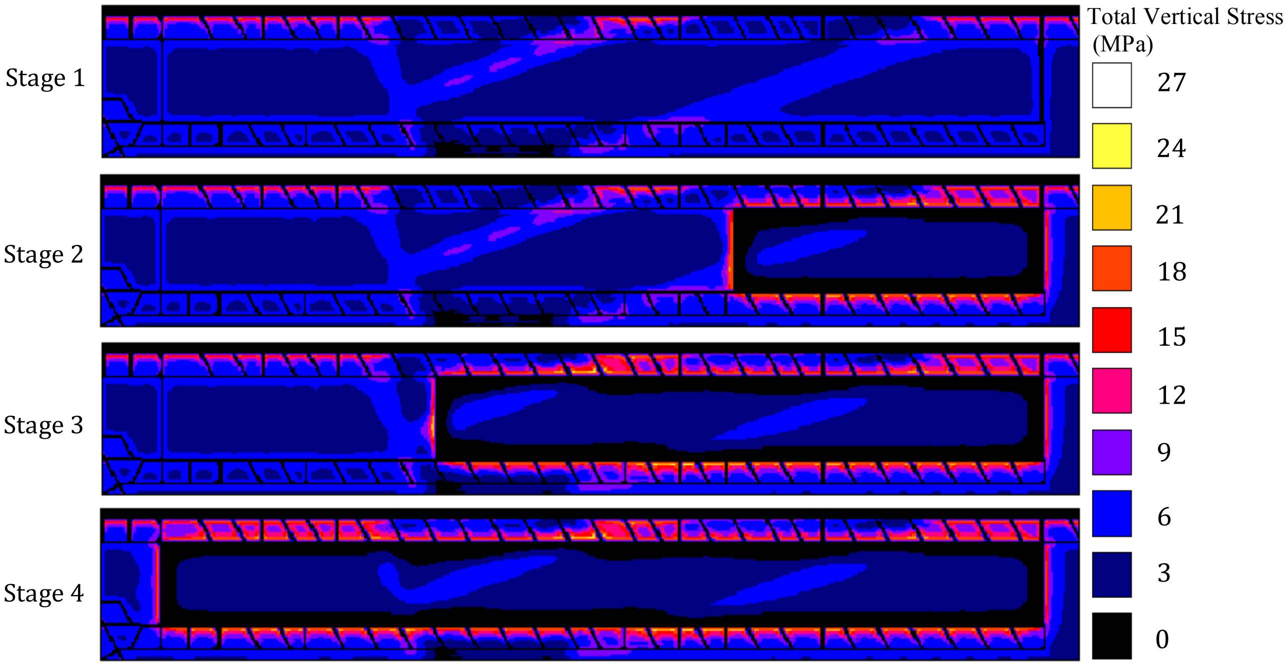


Figure 19. Contour plots of Total Vertical Stress for the LW210 Panel.

The total vertical stress was then plotted for each POI over the stages and is displayed in Figure 20.

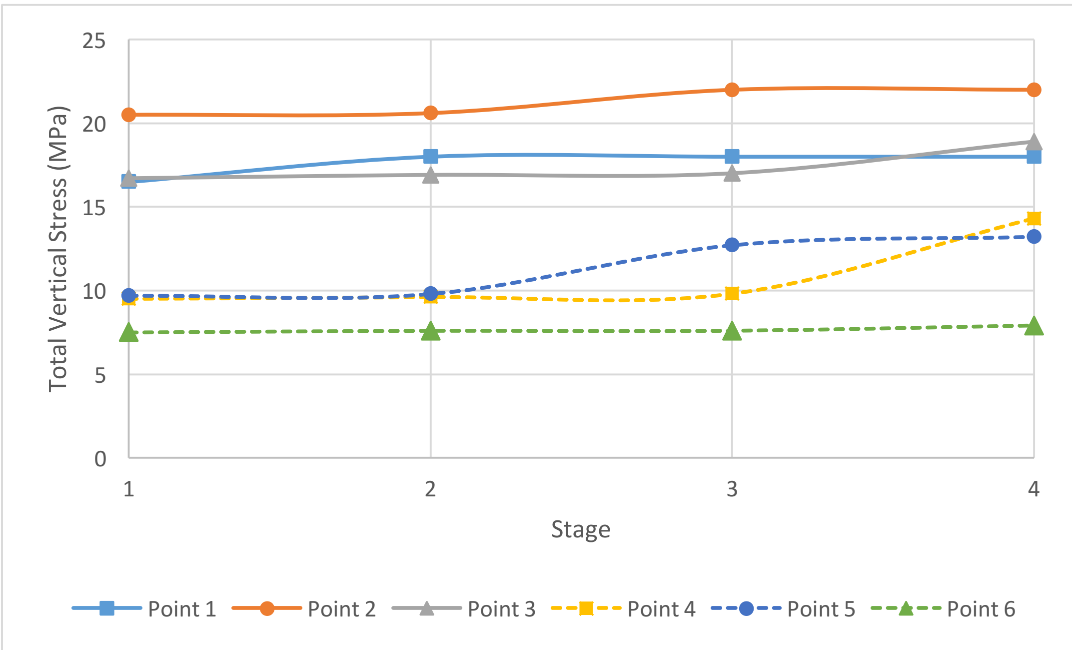


Figure 20. Total Vertical Stress throughout the extraction of LW210.

The pillars on the tailgate side of the panel exhibit higher total vertical stress loads in comparison to the maingate pillars. This is to be expected as the tailgate pillars undergo prior loading from the abutment of the excavated LW209 panel. The stress imposed upon the pillar at Point 6 remains constant throughout the longwall retreat, and exhibits the lowest stress. The stress in the remaining pillars increase at different stages as the abutment stresses are transferred.

5.1.2 Multiple Seam Stress

LaModel calculates the multiple seam stress as the change in the stress on the active seam due only to previous mining in the upper seam. The contour plot of the multiple seam stress shown in Figure 21.

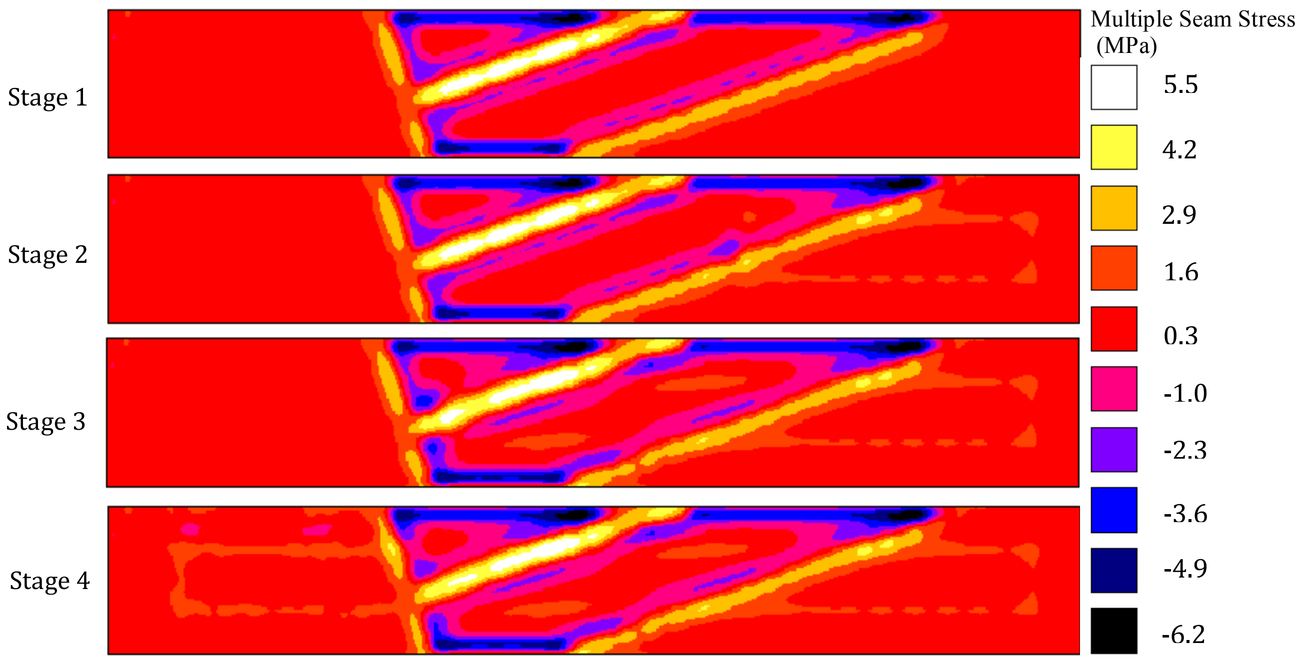


Figure 21. Contour plots of the multiple seam stress for the LW210 panel.

The multiple seam stress was then plotted for the POI and is displayed in Figure 22 below. The multiple seam stress calculated by LaModel shows greater stress beneath areas of increased abutment including the Castor chain pillars and at the edge of the goaf region. Unlike the total vertical stress there is no distinct difference between maingate and tailgate pillars since the abutment from the Argo seam is not taken into account. The maingate pillars exhibit a slight decrease in multiple seam stress as the longwall retreats, this may be due to the direction of principal horizontal stress causing a stress shadow to propagate over the maingate. Point 1 shows zero to negative stress this can be attributed to fact that the overlying chain pillars are adjacent to solid coal which carries some of the abutment load from the longwall. The contour plots display regions of negative multiple seam stress below the longwall goaf these are indicative of stress relief zones created by the goaf such as those proposed by the pressure arch theory.

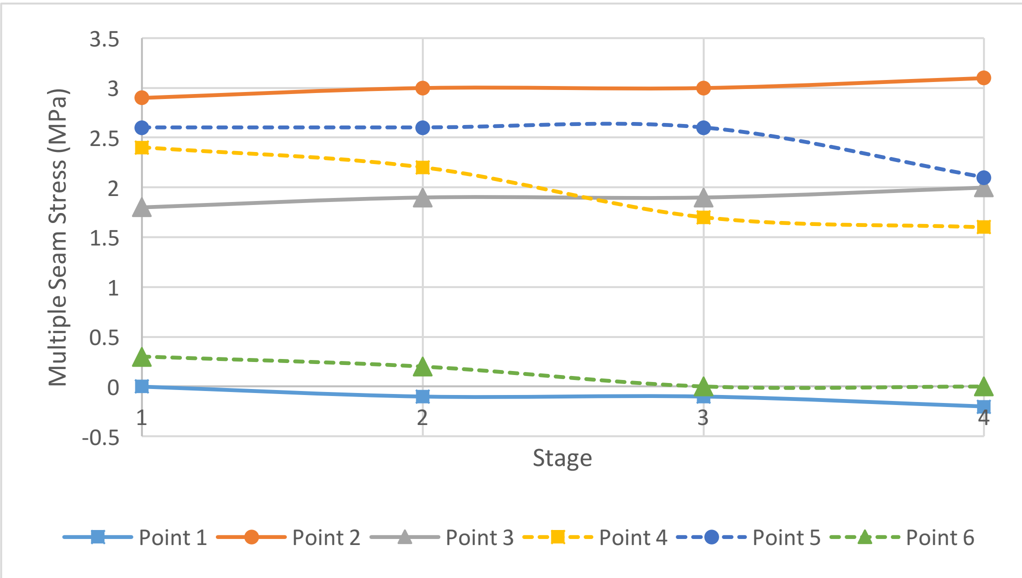


Figure 22. Multiple seam stress throughout the extraction of LW210.

5.1.3 Seam Convergence

The seam convergence is the change in distance (m) between the coal seams due to the total vertical stress. The contour plots of the seam convergence over the four stages are shown in Figure 23.

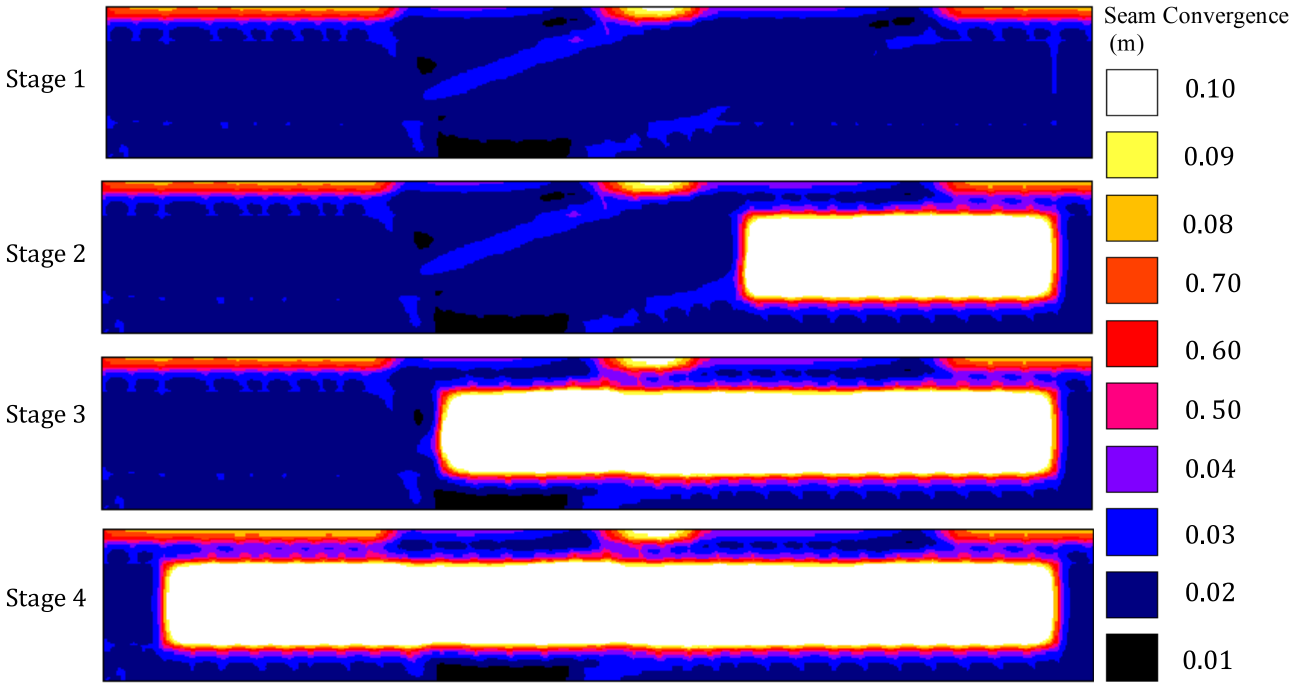


Figure 23. Contour plots of the seam convergence for LW210 panel.

The seam convergence at the POI are shown in Figure 24 for the four stages of extraction. The seam convergence is directly affected by the caving of the overburden behind the retreating longwall. It is therefore expected that as the panel retreats the convergence observed by the chain pillars increase, as is exhibited in Figure 24. The tailgate pillars again demonstrate increased convergence in comparison to the maingate pillars due to the effects of prior caving from LW209. The largest convergence is recorded for Point 5 exhibiting convergence of 0.05m before the longwall passes.

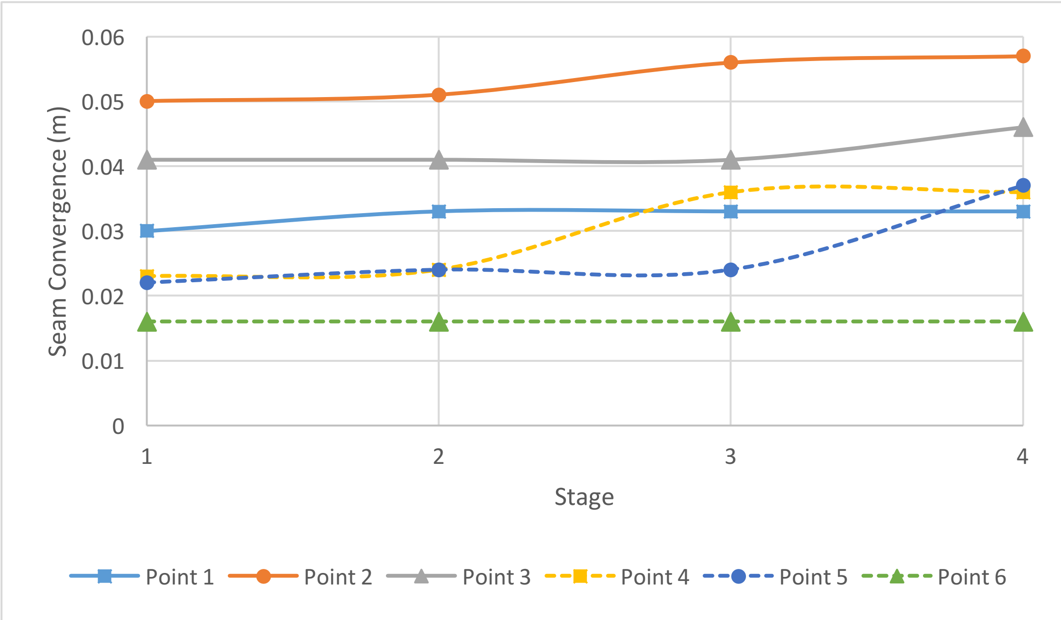


Figure 24. Seam convergence throughout the extraction of LW210.

5.1.4 Pillar Safety Factor

LaModel determines the safety factor as the ratio of the stress applied to elements and the strength of the elements. The safety factor of each pillar is then the average of the safety factor of each element within the pillar. As a result, the pillar safety factor is conservatively low. The pillar safety factor for each stage of LW210 excavation is shown in Figure 25.

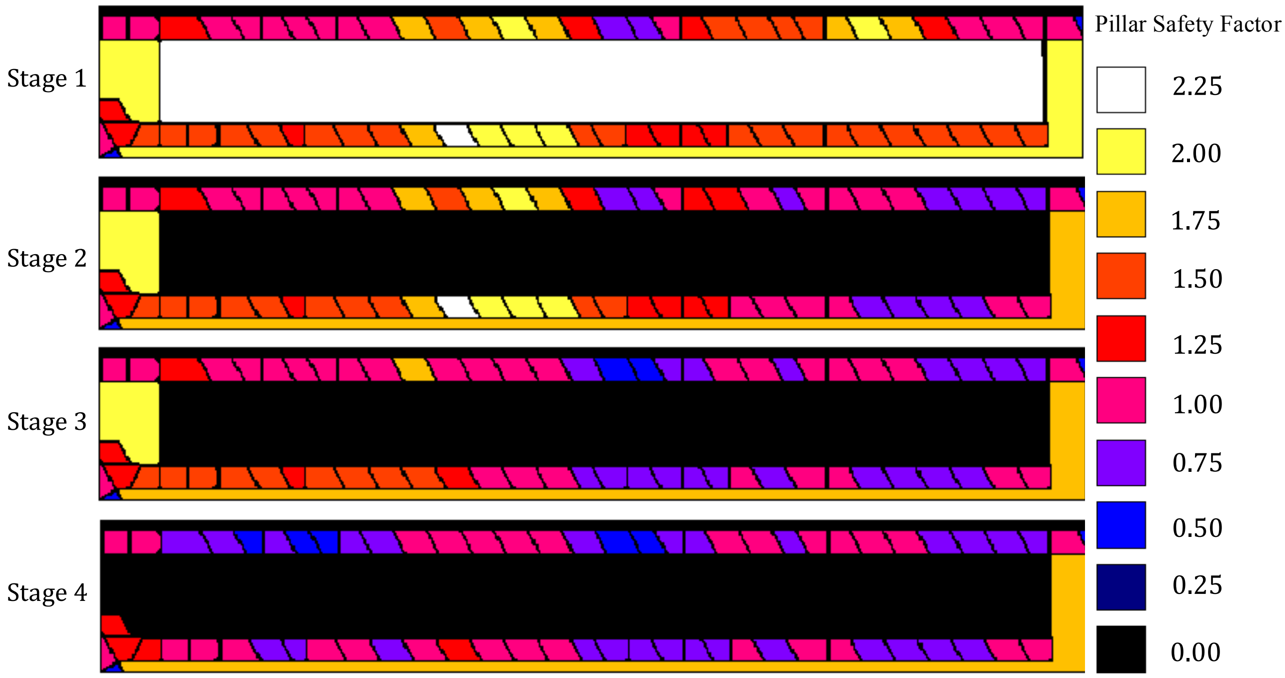


Figure 25. Contour plots of the pillar safety factor for LW210 panel.

The change in safety factor as the longwall retreats is shown in Figure 26. As discussed in Chapter 4, the method of determining the pillar safety factor yields a conservatively low factor of safety. As such, the results show that all POI, including the base point, will fail at some stage of the excavation. This is not a realistic outcome, thus indicating pillar safety factor is not a solely reliable method of determining the risk of geotechnical instability due to multiple seam interactions. However, the pillar safety factor may be used to determine stability of pillars relative to each other. The pillars on the tailgate side of the panel exhibit significantly lower safety factors than those on the maingate side. Point 5 exhibits a very similar trend to the base point however is impacted slightly in stage four by the abutment from the excavated panel. Point 2 is again the most severely affected by the multiple seam interactions exhibiting the lowest factor of safety.

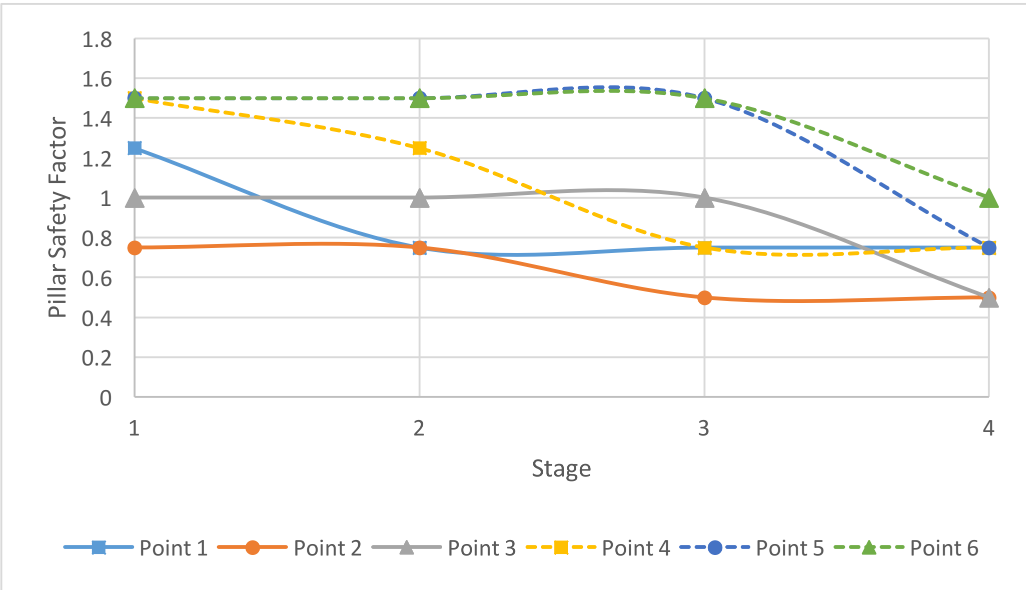


Figure 26. Pillar safety factor throughout the extraction of LW210.

5.2 Combined Panel Model

The process outlined in Section 5.1 above was applied for all thirteen longwall panels. The points of interest for the study are shown on the mine plan in Figure 27.

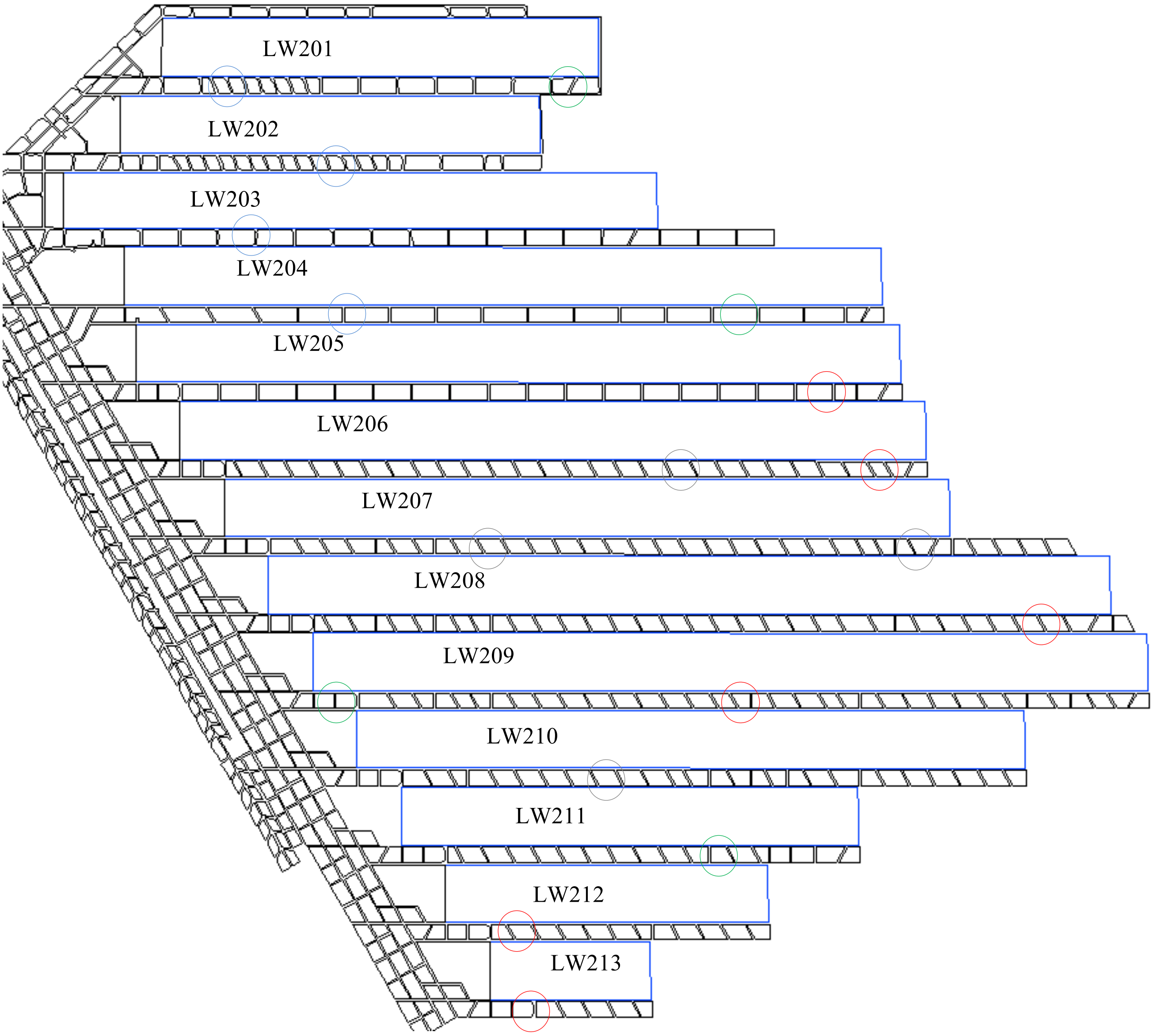


Figure 27. Points of interest for entire Argo seam mine plan

The points of interest are colour coded according to their respective characteristics as follows:

- Green – base points used for comparison;
- Blue – below edge of bord and pillar workings;
- Grey – below longwall chain pillars; and

- Red – below longwall goaf edges.

An effort was made to obtain a distribution of points from below goaf edges, chain pillars and remnant isolated pillars. Four ‘base points’ in regions of no or low multiple seam interaction were chosen across the lease for the purpose of comparison. These points include those from the LW210 example however the numbering has been altered.

The extent of results produced from the analysis are too extensive to provide completely within this report. As such only the key findings will be discussed.

5.2.1 Bord and Pillar Workings

Pillars from the tailgate of LW202-LW205 experienced significant increases in TVS due to complex workings in the overlying bord and pillar workings. Secondary extraction of the Castor pillars resulted in increased stress particularly at the edge of this region. The TVS for the POI are shown below.

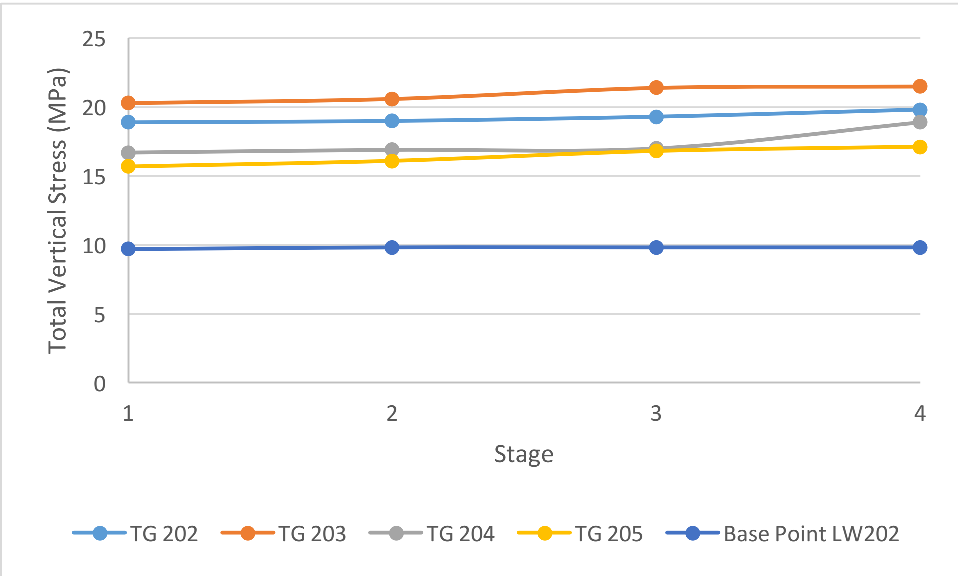


Figure 28. TVS for POI in TG202 to TG 205

5.2.2 Chain Pillars

The pillars that lay beneath the chain pillars experienced severe multiple seam interactions with increased TVS, MSS and seam convergence encountered. The MSS of the POI of the pillars that lie beneath chain pillars are shown in Figure 29 in comparison with the base point in the maingate of LW211. The stress induced on the

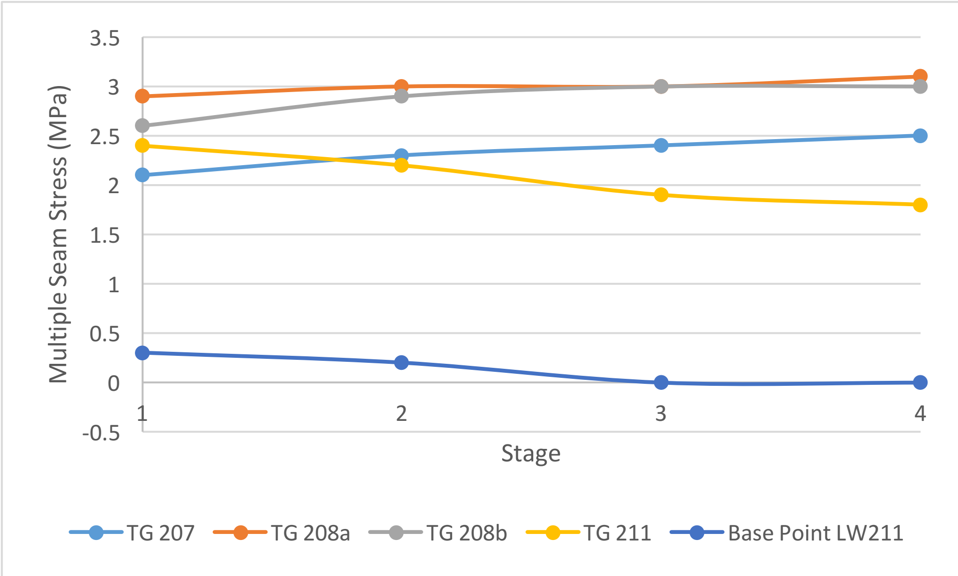


Figure 29. MSS for POI below longwall chain pillars.

pillars due to prior mining exceeds the base point by up to six times. The addition of 3MPa of vertical stress to a pillar can result in significant geotechnical issues if not properly planned for.

5.2.3 Goaf Edges

Significant TVS was also experienced for pillars below the goaf edges of the Castor longwall panels. The results for the POI were compared with the base point in LW212 and are shown in Figure 30. The TVS applied to the panels ranges from 17.8MPa to 19.1MPa. A maximum TVS of 22.6MPa was observed for the pillars in the tailgate of LW209. The pillars in this region exist below a corner of a longwall panel. As such two high stress concentrations occur in close proximity to one another which may result in poor mining conditions. Severe interactions resulting in very poor ground conditions are expected within the tailgate of panel LW208 where the chain pillars also lie beneath the corner of a Castor longwall panel.

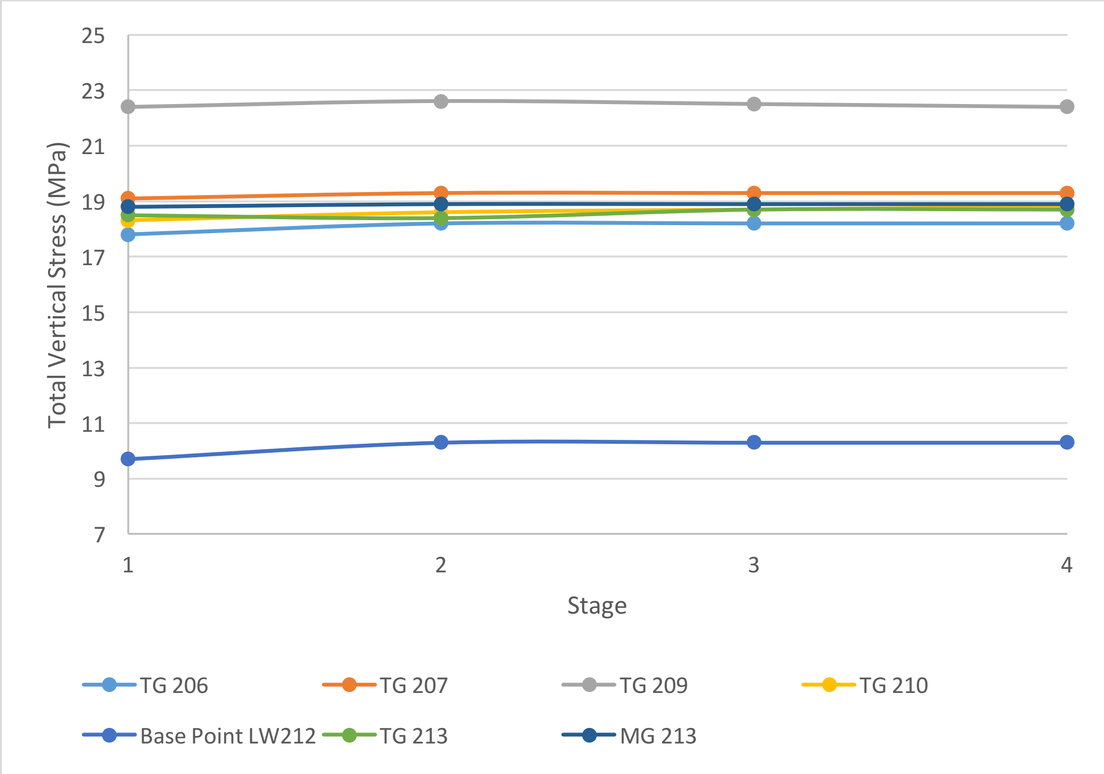


Figure 30. TVS for POI beneath longwall goaf edges of the Castor seam.

5.3 Analysis Of Risk

From the LaModel outputs the risk of increased geotechnical instability due to multiple seam interactions for the gateroads of each longwall panel was assessed. Each panel was assessed individually as it was identified that the pillar stability would be different depending on whether it was a maingate or tailgate pillar. The gateroads were categorised according to the following levels of risk:

- Low (Green): No multiple seam interactions expected.
- Medium (Yellow): Some multiple seam interactions expected resulting in poor ground conditions.
- High (Red): Severe multiple seam interactions expected resulting in very poor ground conditions.

The risk categories define the level of interactions expected, it is recommended that the impacts of multiple seam interactions be investigated further to determine the level of mitigation methods (such as primary and secondary support) required to overcome the interactions. The risk analysis highlights only the risk of poor ground conditions as a result of multiple seam interactions alone. Poor ground conditions may exist in regions of low risk due to other factors. The risk analysis for the example panel LW210 is shown in Figure 31.

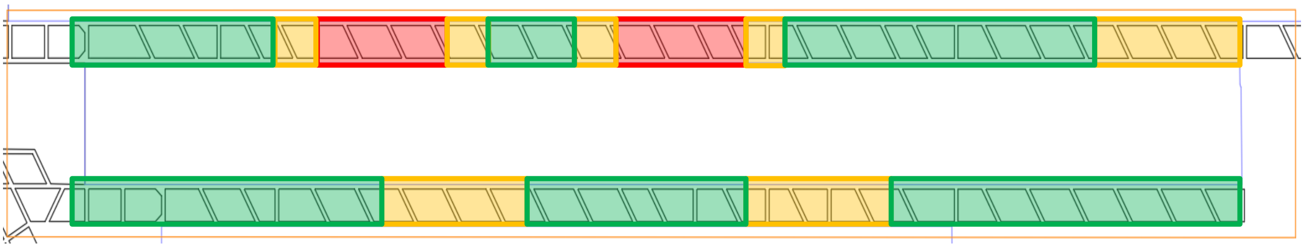
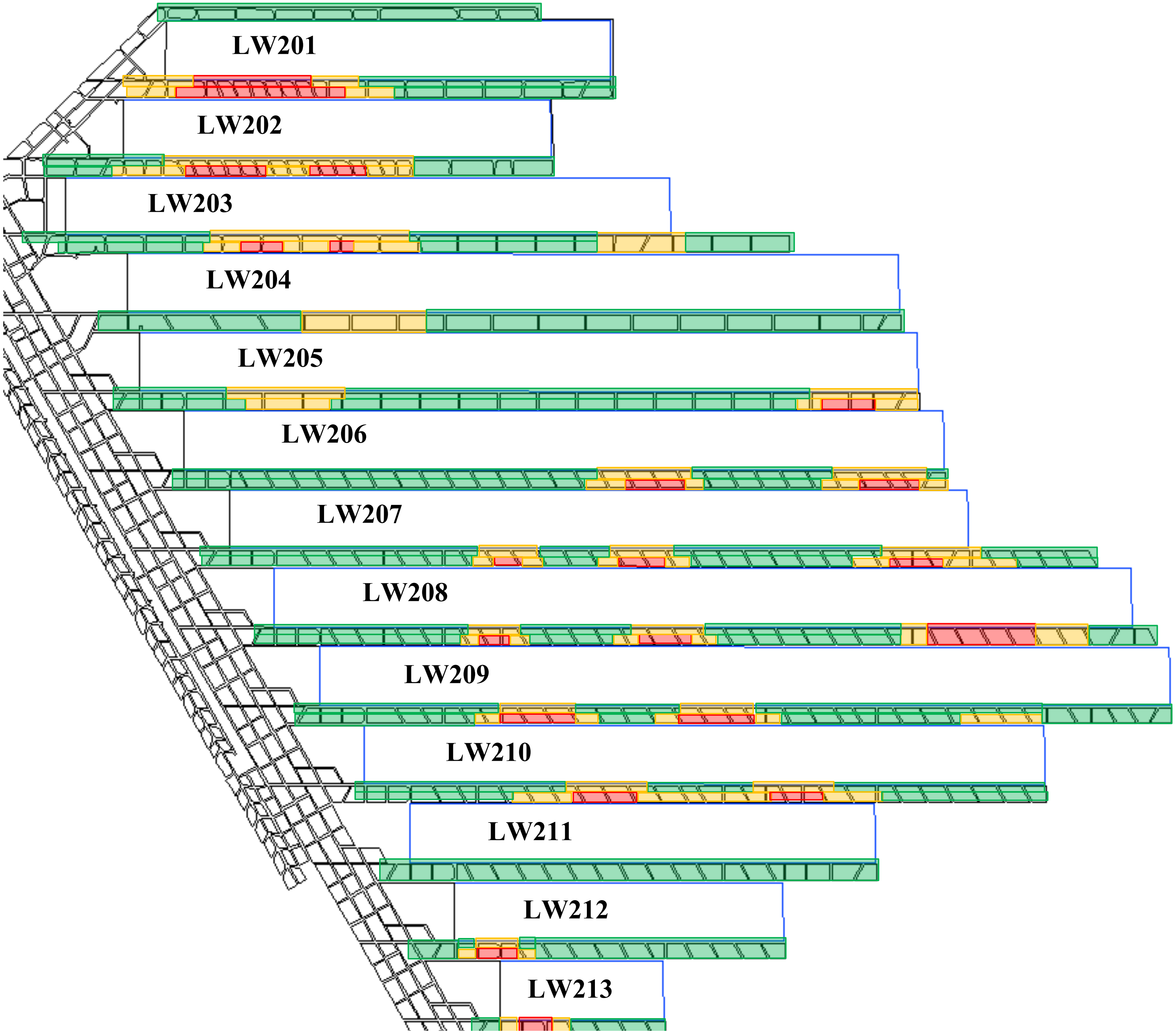


Figure 31. Analysis of the risk of multiple seam interactions in the gateroads of LW210 panel.

Figure 32 displays the thirteen panels and the associated risk.



LW201
LW202
LW203
LW204
LW205
LW206
LW207
LW208
LW209
LW210
LW211
LW212
LW213

The gateroads were split in two to show the change in risk depending on the active panel. In some instances, such as that of LW207 tailgate shown in Figure 33, the risk increases from medium to high due to the increased abutment from the previously mined panel LW206.

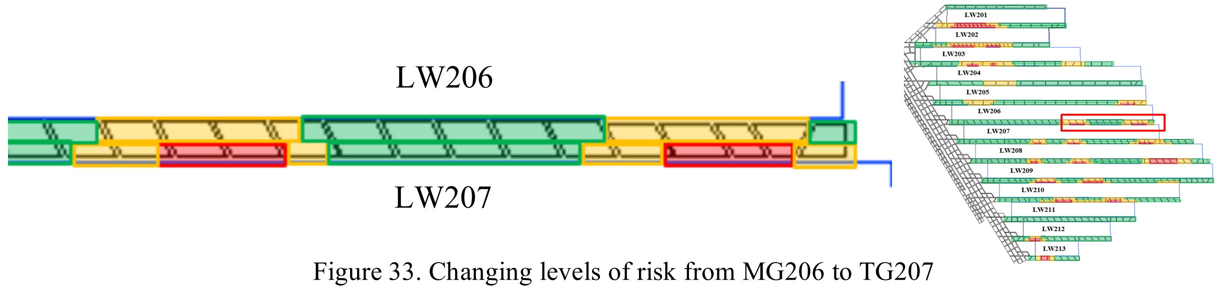


Figure 33. Changing levels of risk from MG206 to TG207

For LW208 and LW209 the pillars exist below the corner of a longwall panel from the Castor seam (Figure 35). The close proximity of the two goaf edge in conjunction with the area of stress relief below the goaf are expected to produce severe ground conditions during the production phases of both LW208 and LW209 as shown in Figure 34. A similar situation exists for the chain pillars between LW207 and LW208. The impact of the high overburden to interburden ratio in these areas is likely to be a major contributing factor to the extent of the multiple seam interactions.

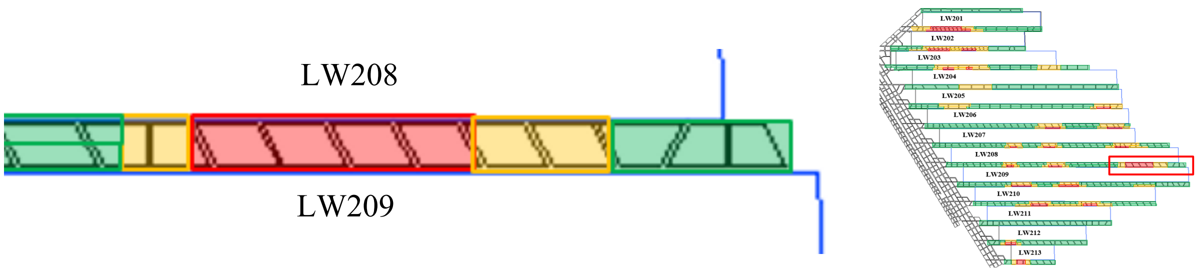


Figure 34. Area of high risk of severe multiple seam interactions in gateroads of LW208 and LW209 panels.

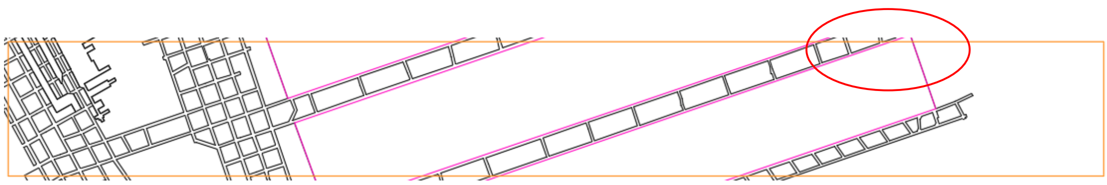


Figure 35. Area of Castor seam workings above LW209 with corner of Castor seam longwall panel that lies above LW208 and LW209 identified.

Complex bord and pillar workings in above panels LW202, LW203 and LW204 (Figure 36) are expected to produce difficult conditions in the tailgate roads of the panels (Figure 37). Furthermore, the small size of the pillars will cause the pillars to be less capable to manage the high total vertical stress resulting in significantly low relative pillar safety factors.

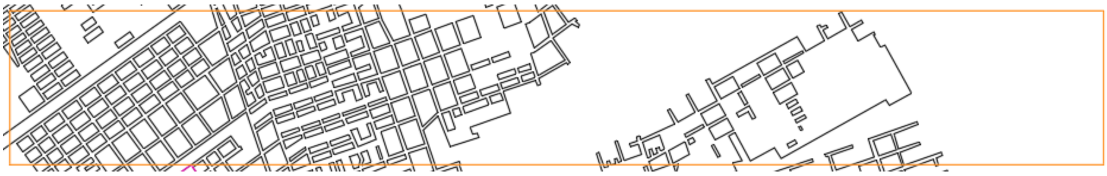


Figure 36. Complex bord and pillar workings in the Castor seam above LW204 panel.

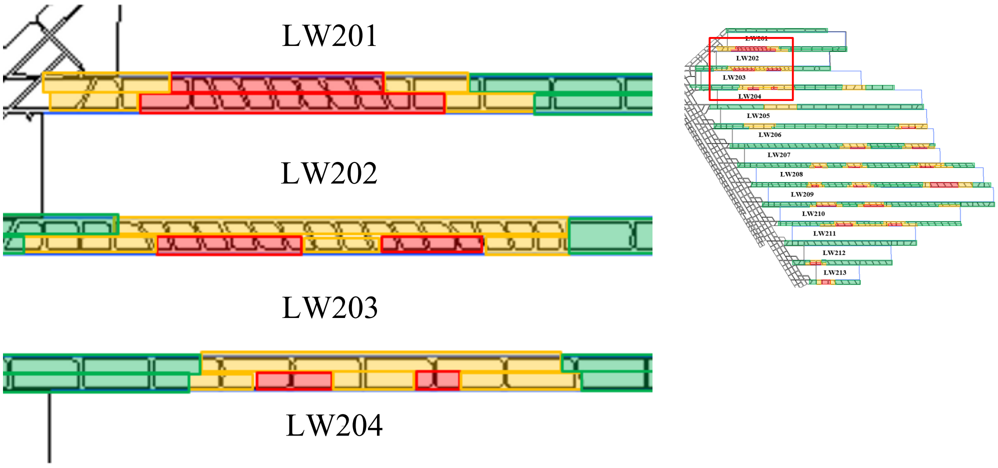


Figure 37. High risk region of Argo seam due to complex bord and pillar workings in Castor seam.

5.4 Model Validation

The validity of the numerical modelling process was assessed by comparison of the model outputs with site experience. At the time of the project, production was occurring in the LW202 panel. As such, the model was validated by experience from LW201. During the mining of LW201 panel, very poor ground conditions were experienced at locations 1 and 2 identified in Figure 38 and poor conditions were experienced at location 3 (Snowman, 2012). The nature of the conditions cannot be discussed within this report.

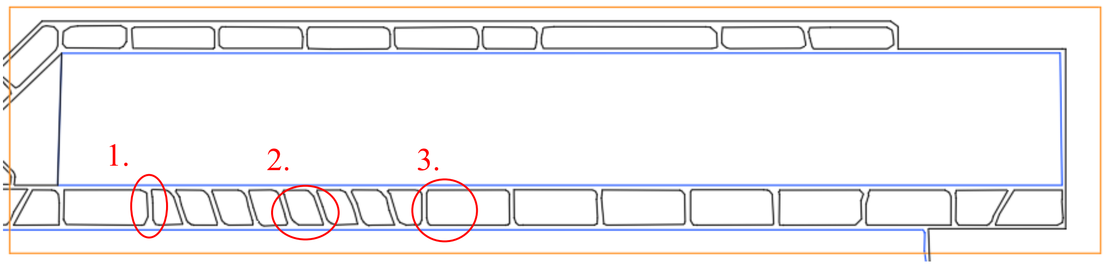


Figure 38. Experienced regions of poor ground conditions for LW201 maingate.

The model identified significant TVS of 18.9MPa, 22.8MPa and 16.5MPa for points 1, 2 and 3 respectively when two-thirds of the panel was extracted. The MSS identified by the model at this stage of excavation was 2.8MPa, 3.2MPa and 2.1MPa for points 1, 2 and 3 respectively. Increased seam convergence was also noted for these regions. The risk analysis of the panel is displayed in Figure 39.

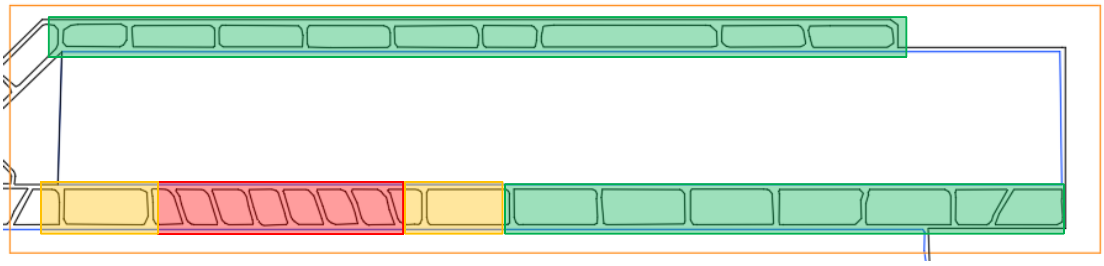


Figure 39. Multiple seam interaction risk analysis for LW201 panel.

The levels of risk associated with the panel identify that the areas where very poor and poor ground conditions and were experienced were highlighted as high and medium risk areas for multiple seam interactions respectively. Without data from site, such as extensometer and stress measurements, the validity of the model cannot be fully commented on, however the model seems to align with experience from the site. It is recommended that the model outputs be compared to experience and data available from LW202 to confirm the validity of the model.

6. CONCLUSIONS

The research project focused on the Cook Colliery multiple seam underground coal operation south of Blackwater, Queensland. The project aimed to quantify the stress induced during development and extraction of the Argo seam as a result of the overlying bord and pillar and longwall workings in the upper Castor seam. The project sought to successfully utlilise numerical modelling to determine the occurrence of multiple seam interactions at the site to allow for appropriate measures to be implemented so that the adverse impacts of the interactions are mitigated.

Multiple theories surrounding the redistribution of stress around excavated areas exist. However, it is generally accepted that the stress will concentrate in remnant pillars and long goaf edges. The influence of the stress concentrations can extend up to four times the pillar widths above and below the isolated pillars. Review of literature surrounding multiple seam operations both in Australia and internationally identified that the major ground control issues resulting from undermining are roof falls, floor heave and rib yielding. The worst conditions were believed to occur during undermining of goaf edges and large remnant or chain pillars.

The displacement-discontinuity, boundary element program LaModel was selected for the purpose of this project. The program is particularly useful for modelling coal seams as it considers the overburden to be laminated rather than an intact rockmass, such is the case with depositional orebodies such as coal. The numerical model yielded results that largely align with the review of literature. The most significant interactions were identified beneath the goaf edges and chain pillars of the castor seam longwall panels. Specifically, in the South East of the lease area where the overburden to interburden ratio is greater. Some major interaction was also identified in the tailgates of the LW202 to LW204 panels beneath very complex bord and pillar workings.

The gateroads of the thirteen longwall panels in the Argo seam were categorised according to their risk of multiple seam interaction. This analysis allowed for the development of a risk map. The interactions at locations of medium and high risk should be further investigated so that appropriate mitigation methods can be established to account for the increased stress. The model was validated against the experience from LW201 panel however further validation should be conducted from stress and extensometer data from the LW202 panel once mining is completed.

7. RECOMMENDATIONS AND FUTHER WORK

A number of limitations of the model were identified throughout the project. The inability of the program to model horizontal stress and displacement due to the assumption of a frictionless laminated overburden does not allow the full extent of the multiple seam interactions to be considered. Though the decreased level of accuracy was adequate for the purpose of this project due to time and financial constraints, it is recommended that further investigation be conducted into the horizontal stress impacts on the geotechnical stability of the workings. The accuracy of the model could also be improved by considering the exact over burden and interburden stratigraphy rather than generalised material properties as it was identified that these have a significant impact on the propagation of multiple seam interactions. Furthermore, investigation into a more appropriate pillar safety factor method should be conducted to confirm the validity of the risk analysis map in Chapter 4. The validation of the model should be confirmed against stress and extensometer data from the extraction of the LW202 panel.

Due to the nature of the research project, the scope of the project does not consider the effects of undermining on the overlying sealed workings in the Castor seam. However, it should be noted that this is a possible direction for further extension of the study.

The project creates a pathway for further work into multiple seam modelling for Australian conditions. Modelling of multiple seam interactions including a comparison of site experiences could be conducted across multiple sites across Australia to establish a database and design guidelines for Australian multiple seam underground coal mining.

8. REFERENCES

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APPENDIX A – MINE PLANS

Figure 40. Mine Plan of Castor Seam.

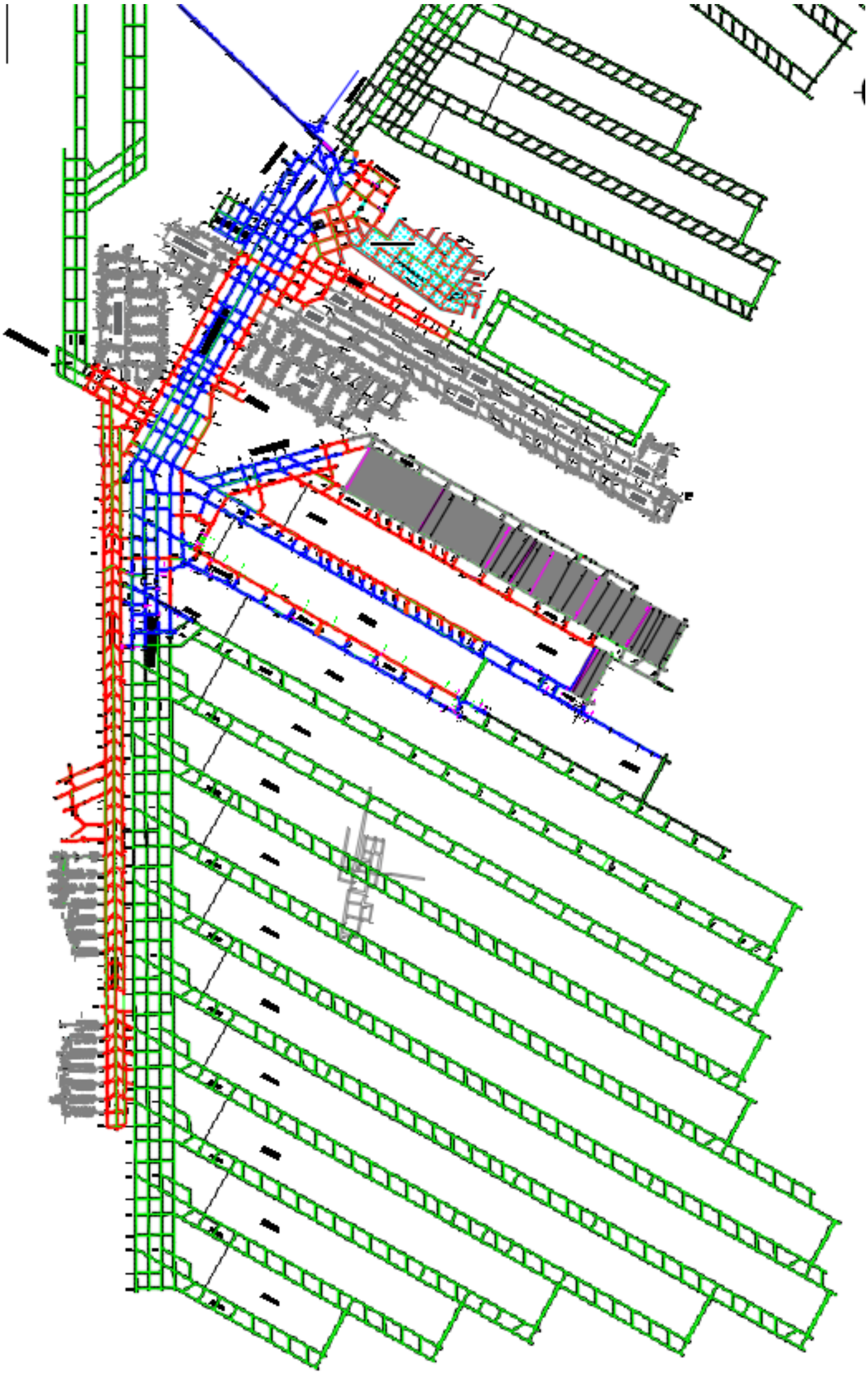

Figure 41. Mine Plan of Argo Seam Longwall Panels.

APPENDIX B – PROJECT PLAN

SCHEDULE

The overall tasks of the project are detailed in Table 5 including the expected completion date of the tasks.

Table 5

. Summary of project tasks.

Task	*Expected Completion Date*
Supervisor Consultation	30/10/2016
Project Proposal	24/03/2016
Annotated Bibliography	22/04/2016
Literature Review	16/05/2016
Progress Report	25/05/2016
Numerical Modelling	10/09/2016
Seminar	22/09/2016
Final Report	10/10/2016
Preparation of Conference Paper	28/10/2016
Completion of Thesis Project	07/11/2016

The tasks that were identified as critical for the timely completion of the project surround the numerical modelling process. The critical path is dependent on the acquisition of required data, set up of the model and generation of reliable results. The risks that could affect the completion of these tasks are assessed below.

RESOURCE REQUIREMENTS

The resources required in order to accurately complete the project are outlined in Table 6 below. Indicative costs have been allocated to the resources however as this is an undergraduate research project there is no allocated budget. The cost of the Academic and Industry supervisors time is estimated from an assumption of 1-hour commitment per week for the life of the project. The student’s time is estimated from a 4-hour commitment per week for the life of the project.

Table 6

. Resources and indicative costs

Resource	*Indicative Cost*
Capable PC	$1500
Student LaModel Licence	N/A
Student AutoCAD Licence	N/A
Data Collection	N/A
Academic Supervisor's time	$2600
Industry Supervisor's time	$2600
Student's time	$5200

The total indicative cost for the completion of the project is $11 900.

Risk Management Plan

The risks associated with the completion of the project are shown in Table 7 below including steps that will be taken to mitigate the risk. The risks were ranked using the risk matrix provided in Figure 42 according to the likelihood of the risk and the severity of the consequence.

		Consequence				
		Insignificant (1)	**Minor (2)**	**Significant (3)**	**Major (4)**	**Severe (5)**
Likelihood	**Almost Certain (5)**	Medium (5)	High (10)	Very High (15)	Extreme (20)	Extreme (25)
	Likely (4)	Medium (4)	Medium (8)	High (12)	Very High (16)	Extreme (20)
	Moderate (3)	Low (3)	Medium (6)	Medium (9)	High (12)	Very High (15)
	Unlikely (2)	Very Low (2)	Low (4)	Medium (6)	Medium (8)	High (10)
	Rare (1)	Very Low (1)	Very Low (2)	Low (3)	Medium (4)	Medium (5)

Figure 42. Risk assessment matrix.

Table 7.

Project risk assessment.

Risk	*Likelihood*	*Consequence*	*Severity*	*Mitigation*	*New Severity*
Not receiving required data	2	5	High	Maintain contact with site and retrieve data early	Medium
Loss of contact with site contact (eg. Leave, resignation etc.)	4	4	Very High	Establish interim or replacement site contact.	Medium
Loss of data (eg. Hard drive failure)	2	5	High	Back up data and modelling on multiple storage devices.	Low
Unexpected results	2	5	High	Conduct modelling early and check in with industry and university supervisor regularly	Medium
Excessive time taken to conduct modelling	3	4	High	Reduce the area to be modelled focusing on anticipated "high risk" areas	Medium

Contingency Plan

Contingency plans were established in response to the risks outlined above so that, should these risks occur, the project may be completed within the allocated time. The risks with their associated contingency plans are detailed in Table 8. The table also details the consequences of each contingency plan.

Table 8.

Contingency plan

Risk	*Contingency*	*Consequence*
Not receiving required data	Assume values for unknown figures	Model accuracy compromised
Loss of contact with site contact (eg. Leave, resignation etc.)	Contact another person on site	The contact may not have the same knowledge but may have access to the required resources
Loss of data (eg. Hard drive failure)	Replace data	Extended time for project completion
Unexpected results or model failure	Focus project on data from site and experience of interactions for a more practical approach	Providing only a qualitative not quantitative analysis of multiple seam interactions
Excessive time taken to conduct modelling	Reduce the area to be modelled	Skewed or limited results therefore decreased reliability of the project

While the accuracy and reliability of the model may suffer, if the contingency plans are implemented it is possible for the project to be completed. Appropriate time has been allocated within the project schedule to allow for the implications of contingency plans such that the project will be completed on time.